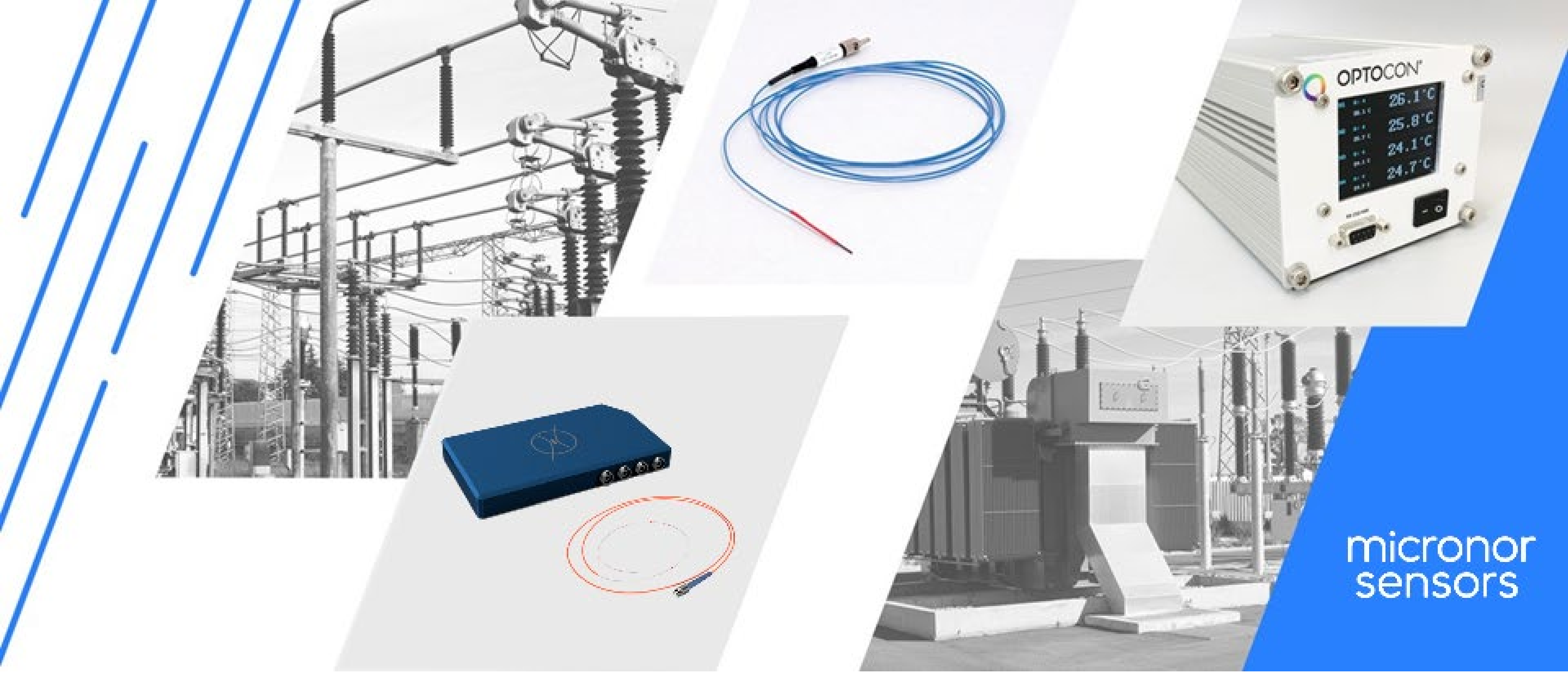


Commercial Fiber Optic Sensors for Temperature and Strain Monitoring

Presented by **Dennis Horwitz**, President

AEMS Seminar Sept 27, 2023

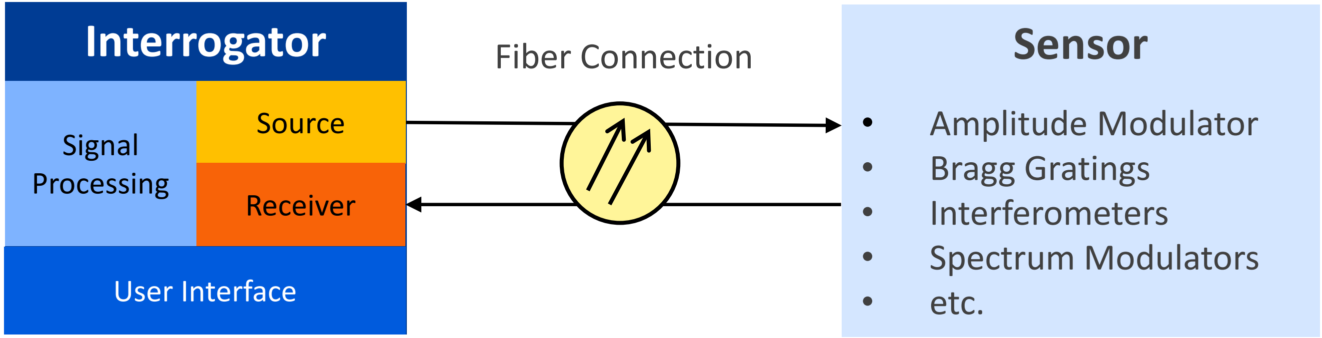
Seminar Outline

- ❑ What is a Fiber Optic Sensor?
- ❑ What is a Fiber Optic Temperature Sensor?
- ❑ High Precision Temperature Sensing with GaAs Thermometry
- ❑ Multipoint Temperature & Strain Sensing with Fiber Bragg Gratings (FBG)
- ❑ Case Study #1: Medical RF Radiotherapy (GaAs)
- ❑ Case Study #2: Medical MRI (GaAs)
- ❑ Case Study #3: Biomedical – RF Induction Heating of Magnetic Nanoparticles (GaAs)
- ❑ Case Study #4: Food Processing – Microwave Ovens (GaAs)
- ❑ Case Study #5: Energy – Health Monitoring of Transformer Hotspots and Bus Bars (GaAs and FBG)
- ❑ Case Study #6: Semiconductor – Better Process Monitoring for Better Yields (GaAs and FBGs)
- ❑ Case Study #7: Medical – RF Ablation Catheter (FBGs)
- ❑ Case Study #8: Overview of other FBG-based Multipoint Applications
- ❑ Basic Fiber Do's and Don'ts
- ❑ Summary – What we learned?
- ❑ Questions and Answers

What is a Fiber Optic Sensor?

“Remote sensing and measuring of a physical quantity using photonics for both sensing and transmission.”

Since most Fiber Optic Sensors are not of transducer[1] type they require an interrogator



➡ Non-electric – No Interference

(1) transducer – a device that converts one form of energy into another.

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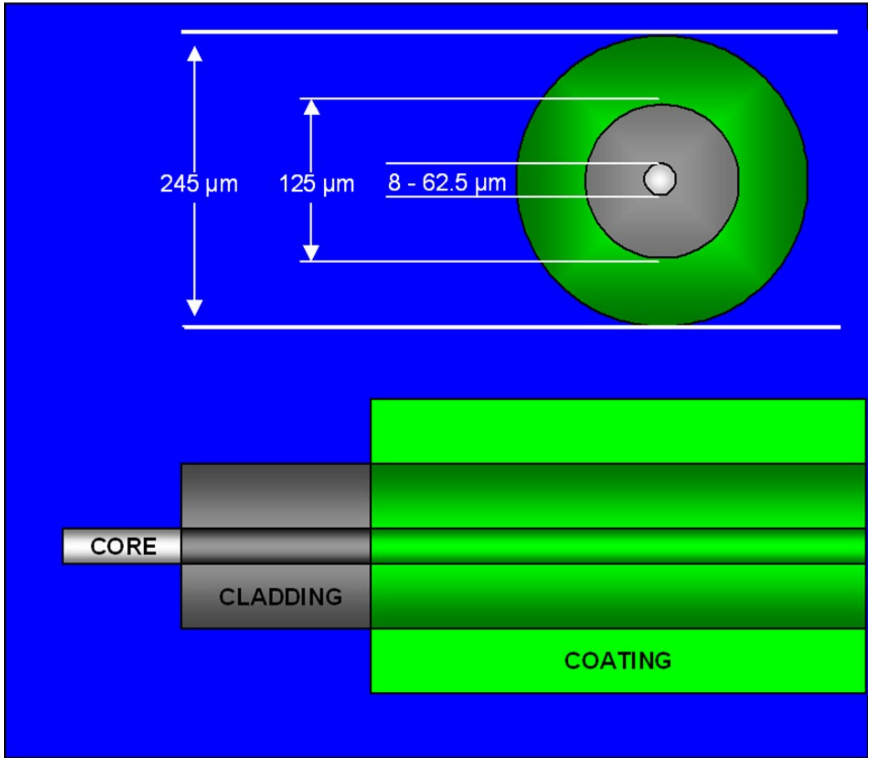
What is Fiber Optics?



Core
- Carries the light signals
- Silica and a dopant, special pure silica core fiber
- POF uses polymer core
- 9µm for telecom SM, 5.6 µm for FiSens SM FBGs
- 50 or 62.5µm for multimode, 1mm for POF

Cladding
- Keeps light in the core
- Pure silicon or polymer

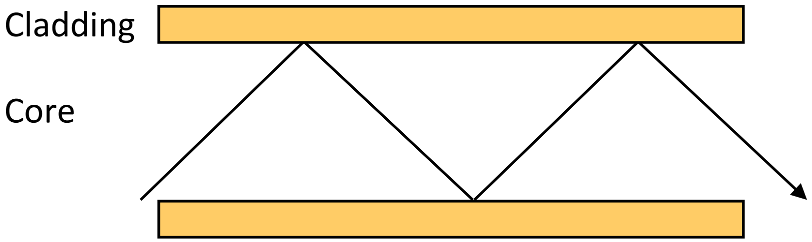
Coating
- Protects the bare fiber
- Acrylate (polymer) or Polyimide (for high temp)

What is a Mode?

What is a mode? Technically, a mode is a stable propagation state in an optical fiber. Dig into mode propagation theory and you will find that it is an effect caused by the wave nature of light.

Forget the technical jargon!

Simply, a mode can be considered as a light ray, or path in an optical fiber.

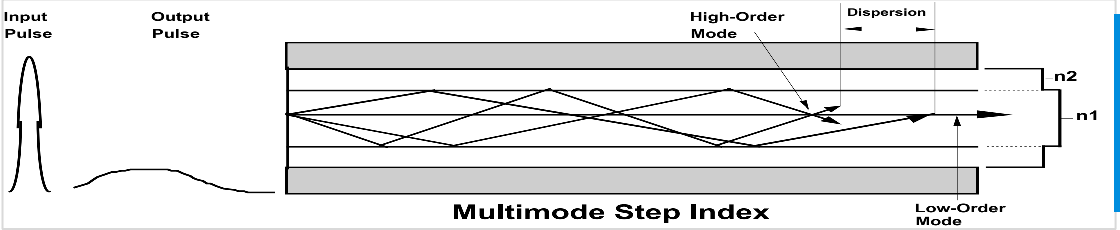


A mode in a step-index multimode fiber

A mode travelling in a singlemode fiber

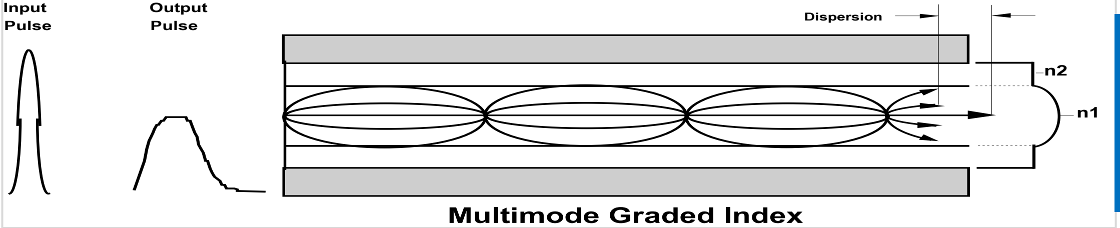
An optical source can emit many modes (light rays) varying by both launch angle and wavelength. Consider how a lamp emits white light (rays) composed of all colors of the spectrum and over a wide area.

What is Fiber Optics?



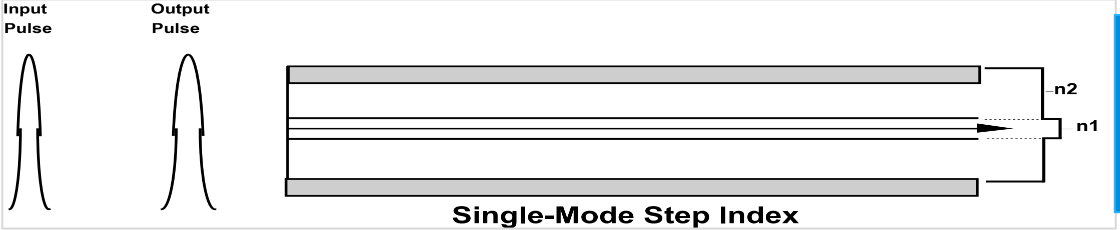
Multimode Step Index Fiber

- Short distance links, <100 m
- 10-100 Mb/s, Single λ
- POF (1mm) or HCS (200/230)



Multimode Graded Index Fiber

- Short-Medium distance links, 10m - 2000m
- 100 Mbs - 10Gb/s, Single λ
- 50/125 (OM2) or 62.5/125 (OM1/OM3)



Single Mode Fiber

- Long distance links, 1000m -100km
- 2.5/10/40/100 Gb/s, Single λ or WDM
- 9/125

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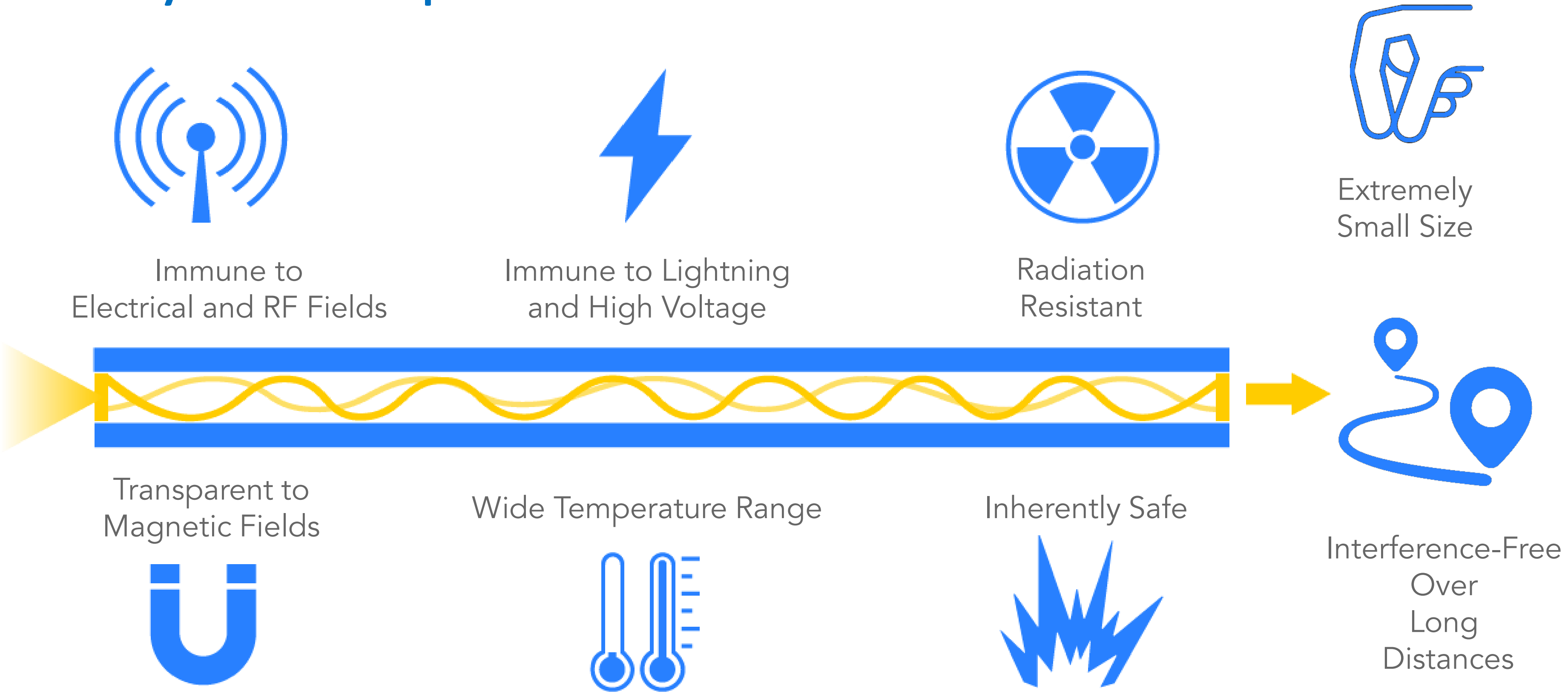
Why Fiber Optics?



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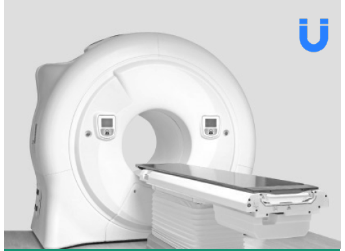
Numerous Applications

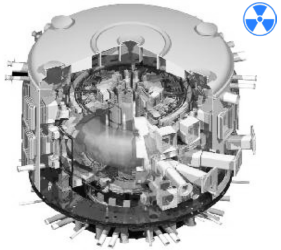

Medical (MRI)

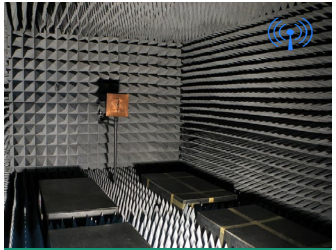

Aerospace

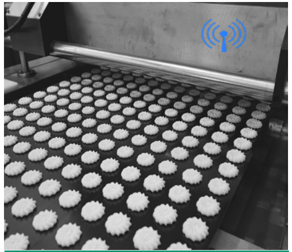

Power & Energy


Life Sciences

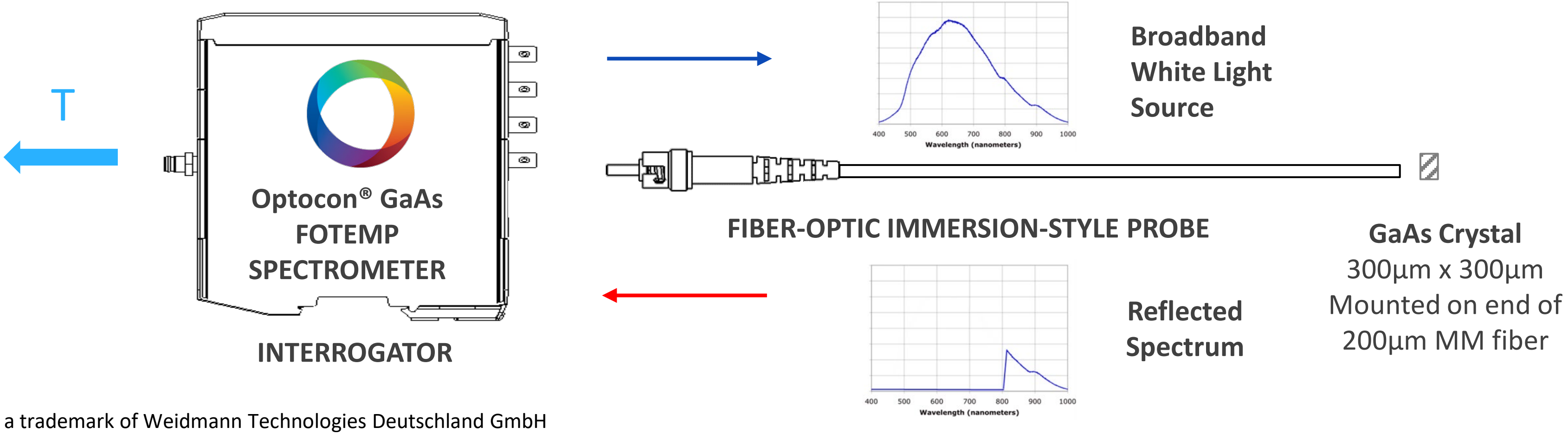

Semiconductor


Nuclear Energy


Test Chambers & Labs


Food & Beverage

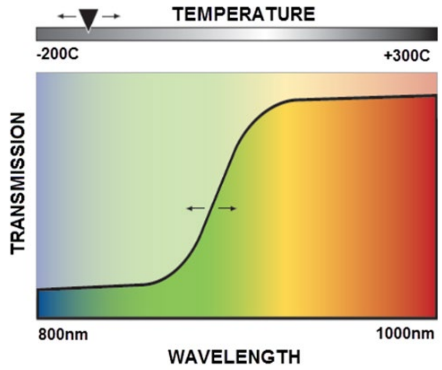
Gallium Arsenide (GaAs) Thermometry



Optocon® is a trademark of Weidmann Technologies Deutschland GmbH

Principles of Operation

1. GaAs is a non-metallic semiconductor crystal in which the effect of temperature is based on the inherent light absorption and transmission properties of the crystal.
2. Light source transmits light to the crystal. Some of the light is absorbed and the rest is reflected back to the spectrometer.



Optical beam probes the wavelength dependence of the intrinsic band-gap of GaAs which is dependent on absolute temperature.

$E_{gap} = 1.423eV$	⇨ 300°K = 872nm
$dE_{gap}/dT = -0.452meV/°K$	⇨ ≈ 0.315nm/°K

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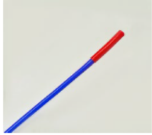
FIBER OPTIC TEMPERATURE PROBES

MODEL	 TS2 General Purpose	 TS3 General Purpose	 TS4 Harsh Chemicals	 TS5 Medical & SFF	 TST Transformers	 TS2p Smallest
Key Features	High Accuracy, Resistance to High Temperatures, Completely Non-Conductive	Semi Rigid Probe, Immune to EMI/RFI and Microwave Emissions	High Accuracy, Corrosion Resistant, Completely PTFE Coated	Flexible Probe, Small Form Factor, and Compact Size	Specifically Designed for Use in Oil-Filled Transformers	Smallest size, Bare GaAs crystal (300µm x 300µm) for Very Small Surface Areas and Micro-Vials
Applications	General Use: Power Transformers and Bus Bar	General Use: Food, Microwave Oven, and RF Environments	Harsh Chemical and Liquid Immersion	Medical Environments, Catheter Instrumentation, Semiconductor, Small FF	Oil-Filled Transformers	General Use: RF, Voltage, Semiconductor Device, and Medical Testing
Temperature Range	–200 °C to +300 °C	–200 °C to +300 °C	–200 °C to +300 °C	–200 °C to +300 °C	–40 °C to +200 °C	–200 °C to +300 °C
Accuracy	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C
Thermal Response	8 °C/s	12 °C/s	7 °C/s	19 °C/s	19 °C/s	20 °C/s
Probe Dimensions	D1: 1.0 mm D2: 1.7 mm D3: 1.3 mm	D1: 1.0 mm D2: 1.7 mm D3: 1.3 mm	D1: 1.0 mm D2: 1.7 mm D3: 1.3 mm	D1: 0.6 mm D2: 2.0 mm D3: 1.3 mm	D1: 1.75 mm D2: 1.2 mm D3: 3.1 mm	D1: 0.25 mm D2: 1.7 mm D3: 1.3 mm
Fiber Optic Cable Dimensions Other length on request	L1: 10 mm L2: 10 mm L3: 1 – 20 m	L1: 10 – 130 mm L2: 30 mm L3: 1 – 20 m	L1: 15 - 550 mm L2: 10 mm L3: 1 – 20 m	L1: 10 – 600 mm L2: 15 mm L3: 1 – 20 m	L1: 10 mm L2: 70 mm L3: 1 – 20 m	L1: 4mm L2: 10 mm L3: 1 – 20 m
Cable Coating	Polyimide / Teflon	Polyimide / Teflon	Polyimide / Teflon	Polyimide / Teflon	Polyimide / Teflon	Polyimide / Teflon
Connector Type	ST	ST	ST	ST	ST	ST
STOCK PRODUCTS (L1 and L3 Lengths)	TS2-02, TS2-06	TS3-10MM-02 TS3-10MM-06	TS4-15MM-02	TS5-20MM-02, TS5-20MM-06 TS5-50MM-02, TS5-50MM-06	Special Order	TS2p-02

98-OPTC-27-C
QR Code to TS sensors

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VENTURA, CA 93003 USA

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sales@micronor.com

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FOTEMP® FIBER OPTIC SIGNAL CONDITIONERS

MODEL	 FOTEMP-PLUS Most Popular!	 FOTEMP-H2 Available 4Q23	 FOTEMP-OEM	 FOTEMP-MINI 2	 FOTEMP-T2	 FOTEMP-MODULAR
Description	Compact Bench Top	Handheld	OEM Module, Bench Top, Chassis or DIN Rail Mount	Small Form Factor OEM PCB Module	DIN Rail, Chassis Mount or Bench Top	Multichannel Modular System
No. of Channels	1, 2 or 4	1 or 2	1, 2 or 4	1	1, 4, 8, 12, or 16	1-255
Measurement Range	−200 °C to +300 °C with C-Calibration	−200 °C to +300 °C with C-Calibration	−200 °C to +300 °C with C-Calibration	−200 °C to +300 °C with C-Calibration	−200 °C to +300 °C with C-Calibration	−200 °C to +300 °C with C-Calibration
Accuracy	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C	± 0.2 °C
Applications	Laboratory	Laboratory and Portable Applications	Laboratory, Process or Transformer Monitoring	Embedded OEM Application	Laboratory, Process or Transformer Monitoring	Laboratory or Process Monitoring
Sample Rate/channel	250ms	250ms	250ms	250ms	250ms	250ms
Internal Data Logging?	No	Yes	No	No	Yes Requires programming via Modbus	No
Data Logging Storage	---	MicroSD Card	---	---	MicroSD Card	---
Analog output	Std=0-10V Option=4-20mA	---	Std=0-10V Option=4-20mA	---	Std=4-20mA (First 8 Channels Only)	Option: 0-10V or 4-20mA
Relay output	Option=4	---	Option=4	---	Std=4	Option=1-255
Interface	Std=USB & RS232 Option=USB & RS485	USB-C	Std=USB & RS232 Option=USB & RS485	USB	Std=USB+ModbusRTU Option=USB+ModbusTCP	Options: ST
Power Supply	12VDC or 100-240 VAC	12VDC or USB-C, nternal Li-Ion Battery	12 VDC	7-12VDC	24VDC	100-240VAC
STOCK PRODUCTS A-CAL= -40°C to +200C B-CAL= -40°C to +300°C C-CAL= -200°C to +300°C	FOTEMP4-PLUS P0-V-B FOTEMP4-PLUS-P0-V-C	FOTEMP2-H2-P0-B	Special Order	Special Order	Special Order	Special Order

98-OPTC-28-C
QR Code to FOTEMPs

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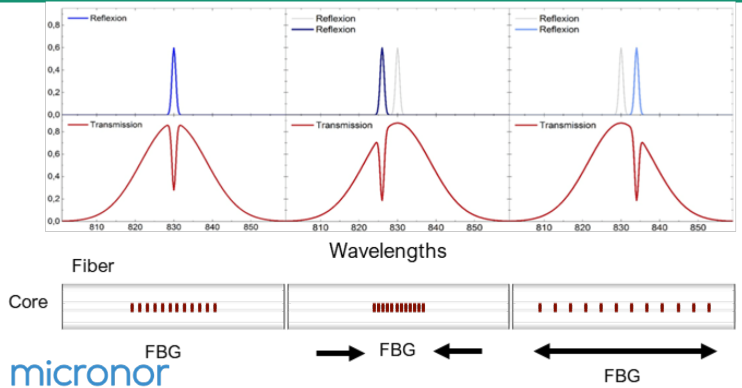
Strain & Temperature via Fiber Bragg Gratings (FBG)

FiSens® FBG System: Interrogator + Fiber Sensor Chain

FiSens® is a trademark of FiSens GmbH

Principles of Operation



1. Ultra-short fento-second laser pulses create high-precision nanoscopic FBG structures into the core of a single mode fiber
2. Multiple FBGs can be written anywhere along the length of the fiber, each tuned to a specific wavelength signature.
3. **Thermal and mechanical force** induce change in the specific reflected FBG wavelengths.
4. FBG Interrogator (integrated light source and spectrometer) analyzes the wavelength shift and converts to temperature or strain.

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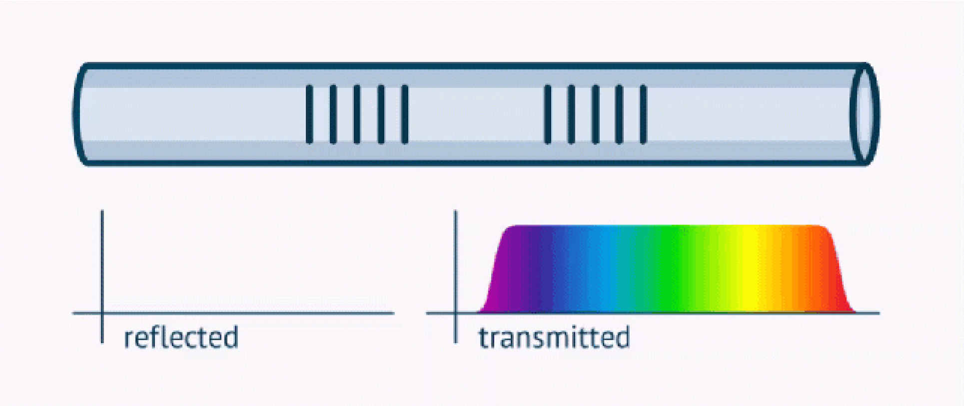
Single and Multipoint Sensing - FBGs



Reflected wavelength of a particular FBG is a function of both temperature and strain on that FBG.

For FiSpec FBGs and interrogators operating at in the 850nm window, the Reflected Wavelength equals Bragg Wavelength which corresponds to 21°C and 0 με (μm/m).

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Theory of Fiber Bragg Grating Sensors

Wikipedia-Fiber Bragg Gratings

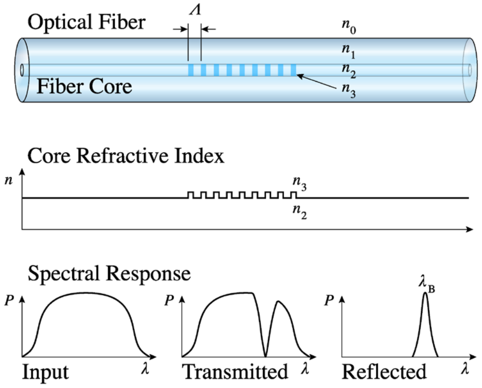

Figure 1: A Fiber Bragg Grating structure, with refractive index profile and spectral response.

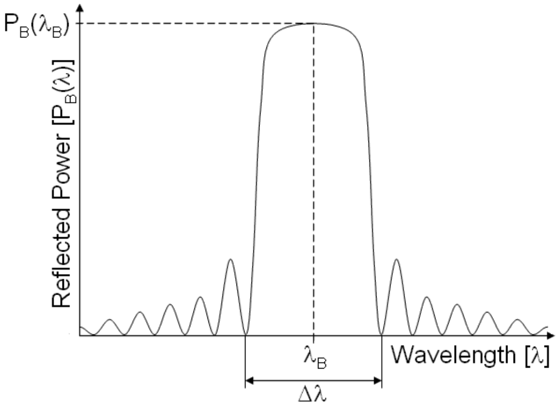

Figure 2: FBG reflected power as a function of wavelength

$$\lambda_B = 2n_e\Lambda$$

The reflected wavelength (λ_B), called the Bragg wavelength, is defined by this relationship, where η_e is the effective refractive index of the fiber core and Λ is the grating period. The effective refractive index quantifies the velocity of propagating light as compared to its velocity in vacuum.

The Bragg wavelength is sensitive to both strain and temperature. The relative shift in the Bragg wavelength $\Delta\lambda_B/\lambda_B$, due to applied strain ε and and a change in temperature ΔT is approximately given by:

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = C_S\epsilon + C_T\Delta T$$

or,

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = (1-p_e)\epsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

where:

C_S is the coefficient of strain and related to the strain optic coefficient p_e; and

C_T is the coefficient of temperature, which is made up of the *thermal expansion coefficient* of the optical fiber α_Λ and the *thermo-optic coefficient* α_η.

FiSens Bragg Grating Sensor Calculations

FiSpec Interrogators – How FBG Temperature and Strain are Calculated in Firmware

When purely mechanical stress is applied to an FBG („strain FBG“), the respective strain value can be calculated out of the wavelength shift of the FBG during this process:

$$\varepsilon_S = \frac{10^6}{OEK}\left(\frac{\lambda_S}{\lambda_{S,0}} - 1\right) \qquad \left[\frac{\mu m}{m}\right]. \qquad (1)$$

ε_S = strain (in µm/m) at the strain FBG‘s location

λ_S = actual wavelength of the strain FBG

$\lambda_{S,0}$ = wavelength of the strain FBG at „strainless“ state

OEK = optoelastic constant (≈0.776)

If an FBG is mechanically decoupled from its environment, the wavelength changes because of thermal effects only. Therefore the temperature can be calculated out of the wavelength shift:

$$\vartheta = \frac{1}{TEK}\left(\frac{\lambda_\vartheta}{\lambda_{\vartheta,0}} - 1\right) + \vartheta_0 \qquad [°C]. \qquad (2)$$

ϑ = actual temperature [°C] of the temperature FBG

λ_ϑ = actual wavelength of the temperature FBG

$\lambda_{\vartheta,0}$ = wavelength of the temperature FBG at known temperature ϑ_0

ϑ_0 = temperature [°C] when determining $\lambda_{\vartheta,0}$

TEK = thermoelastic constant (≈$8.65 \cdot 10^{-6} K^{-1}$)

Measuring Range is affected by # of FBGs

Measuring range is affected by the number of FBGs and their spectral separation in a sensor chain:

For Strain - Wide Configuration

		Array																													
Channel	WL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	805 Kompensation																														
1	810	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	812.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
3	815	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
4	817.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
5	820	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	822.5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
7	825	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
8	827.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
9	830	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
10	832.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
11	835	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
12	837.5	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	840	0	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	842.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	845	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	847.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	850	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	852.5	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	855	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	857.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	860	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	862.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	865	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
24	867.5	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25	870	0	1	1	1	1					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	872.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	875	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
28	877.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
29	880	0	0	0	1	1	0	0	0	0	0	1	1	1	1	1							1	1	1	1	1	1	1	1	1
30	882.5	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
31	885	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
32	887.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Bragg Wavelength corresponds to 21°C and 0 με.

For FBGX100 series, the available Wideband spectrum (808- 880nm) is divided into 30 channels corresponding to the usable optical power of the LED source.

Based on # of FBGs required, each FBG is assigned a unique spectral channel based on optimization of optical power (higher power is better) AND spectral spacing (wider spacing provides better wider measurement range).

Strain Coefficient: 0.776 pm/με
Temperature Coefficient: 8.65 pm/K

1-FBG (SW= ±30nm) = ±38,659.8 με or ± 3,468 °C
10-FBG (SW= ±1.8nm) = ±2,963.9 με or ± 208.1 °C
30-FBG (SW= ±0.8nm) = ±1,675.3 με or ± 92.5 °C

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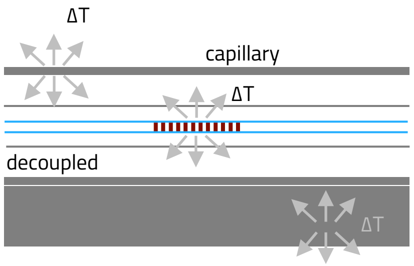
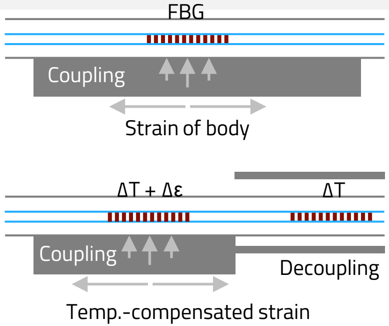
FBG Temperature and Strain Application Guidelines

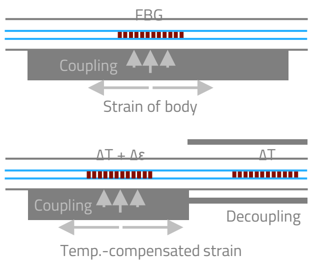
Parameter	Temperature, T	Strain, ϵ
Geometry	Strain-relieved bare fiber or rigid capillary	Bare fiber
Mounting	Inside capillary, secure in machined channel, secure with Kapton tape	Embedded in material, glued to surface
Challenges	Strain also enlarges FBG	Temperature affects refractive index of the FBG, enlarges FBG
Solutions	Choose geometry to avoid strain-related effects	Compensate for thermal expansion with 2nd FBG
Typical Applications	Structural health, wind turbine, switchgear, winding hot spot, injection molding	



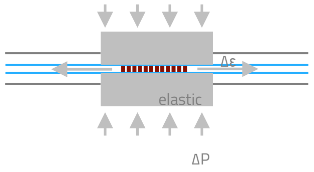


FBG Measurement Applications

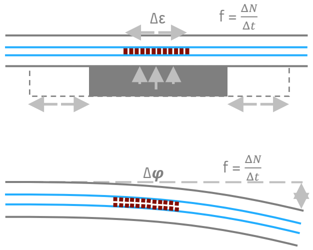
Strain



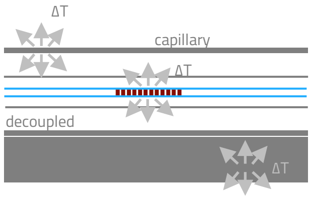
Pressure



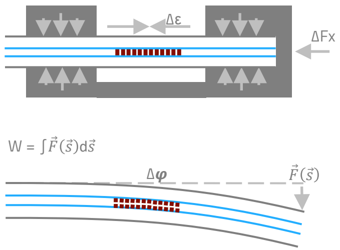
Vibration



Temperature



Force



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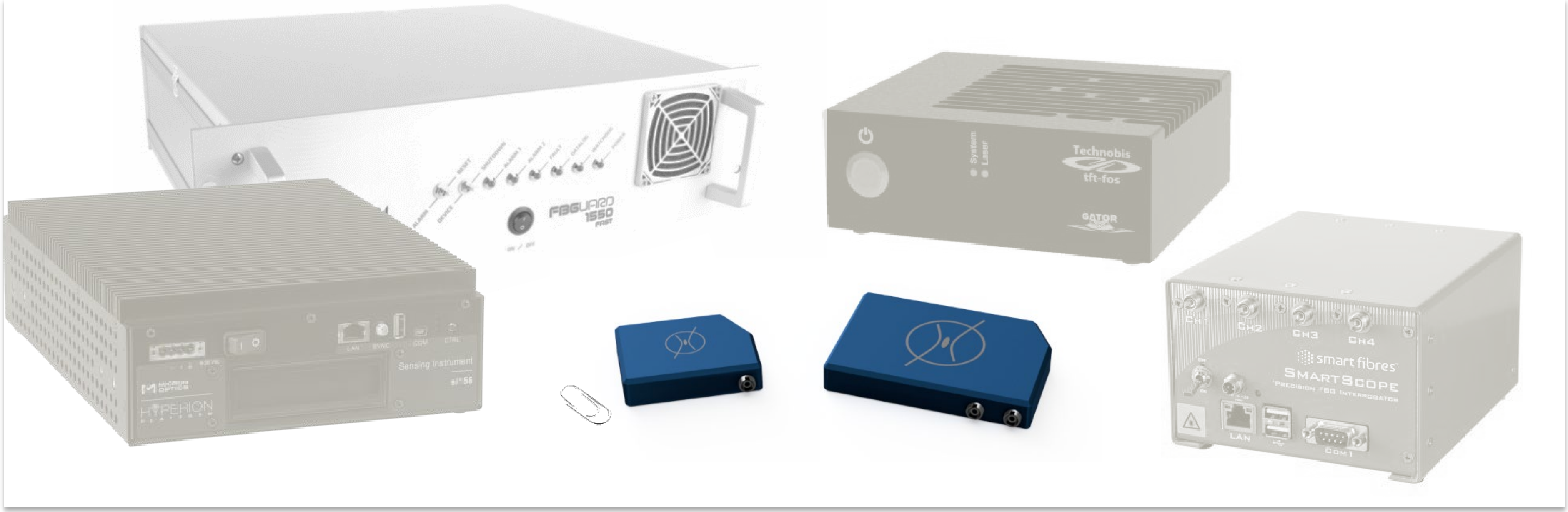
FiSens FiSpec 850nm FBG Sensing System

1/10 the size and 1/4 the cost while maintaining highest performance



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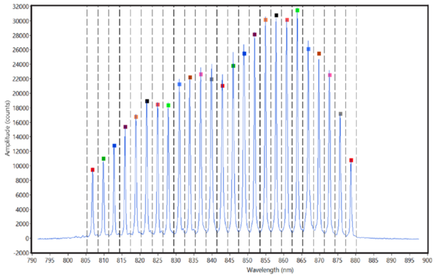
Flagship FiSpec FBG Interrogators (850nm Window) FBGX100 and 4-Channel FBGX400

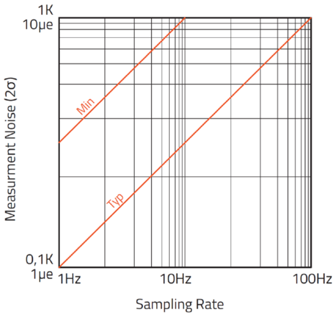
Radical innovative design for mass market FBG-analysis

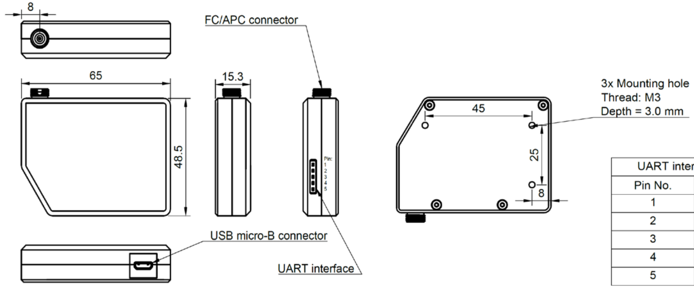
- Worldwide smallest and most economical interrogation system for mutiple FBGs (array) with embedded light source
- Interrogate up to 30 FBGs per channel, Wideband, 808-880nm
- Sampling rate 1-100 Hz (applies to all FBGs)
- Measurement precision : 0.1° or 1µe (at 1Hz)
- Digital Measurement Resolution: 0.001°C or 0.01µe
- Interfaces: Micro-USB, 3.3V UART Port

Exemplary FBG Spectrum @ 850nm



Precision vs. Sampling Rate





UART interface layout	
Pin No.	Signal
1	+5V
2	+3.3V (output)
3	GND
4	RX
5	TX

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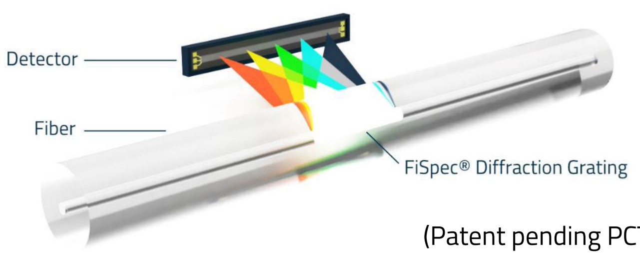
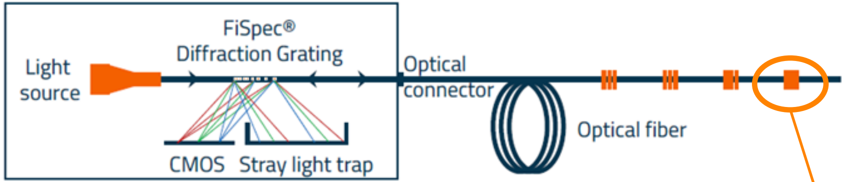
Fiber Integrated FBGX100 Spectrometer

All optical components of a spectrometer within a single optical fiber

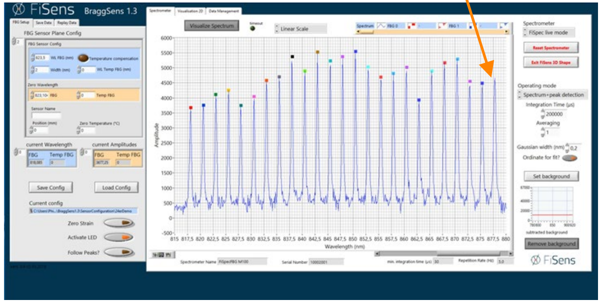
- Unique in-core grating for outcoupling and directly focusing onto image sensor with ultra-high diffraction efficiencies and light intensities
- FBGX100 series can interrogate up to 30 FBGs, over **Wideband (W)** 808-880nm spectrum, 1-100Hz sample rate
- FBGX1000 series can interrogate up to 25 FBGs, over **Narrowband (N)** 808-865nm spectrum, 1-2000Hz sample rate
- Measurement precision : 0.1°C or 1με
- Quasi-monolithic design for highest shock-resistance and thermal stability
- FiSens patented technology



(Patent pending PCT/EP2018/054170)



Single channel BraggSens and multichannel FBG-Interoogator software supplied, include data logging function



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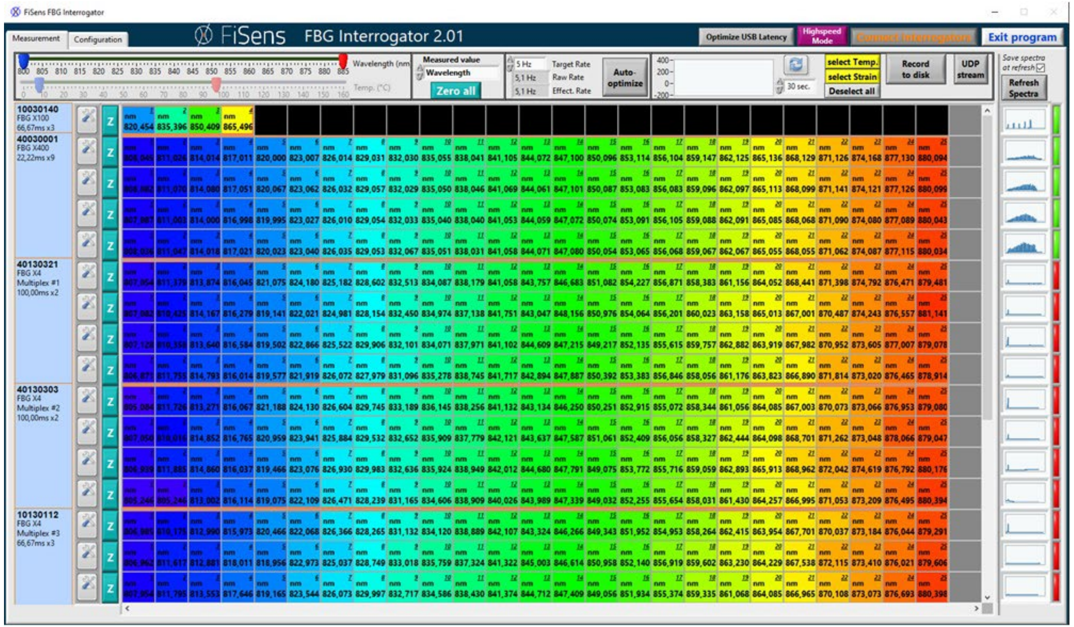
How to read the temperature/strain data

- FiSens **FBG-Interrogator** software is general purpose research tool based on LabView® Runtime and provided FREE. Provides data visualization and data logging functions. It recognizes multiple as well as multichannel interrogators.
- Data logging mode outputs an Excel-compatible tab-delimited CSV file.
- Wideband FBGX100 series (max 30 FBGs per sensor chain) provides built-in microUSB and TTL UART interfaces.
- Narrow Band FGBX1000 series (max 25 FBGs per sensor chain, available 4Q2023) provides built-in microUSB, RS485 and Ethernet interfaces.
- For integration of interrogator communicaditons into customer software, program code examples are provided in NI LabView®, C and Python.




```
Tab delimited data. Strain: [S]=µm/m; Temperature: [T]=°C; Wavelength: [W]=nm;
                                                              Intensity: [I]=ct.
Time(YYYYMMDDHHMMSS.SSS)   10020179/-/1/T1    10020179/-/1/S2   40020423/-/2/T5
20220330092516,9141        31,8400            75,2739           30,9000
20220330092517,8984        32,0700            76,8101           30,8100
```

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FISENS® FBG INTERROGATOR & SENSOR CHAIN QUICK GUIDE

MODEL	FBGX100 Interrogator	FBGX400 Interrogator	FI Sensor Chain Bare Fiber Capillary	PE Sensor Chain PEEK Capillary	SI/AC Sensor Chain SI=Silica, AC=Al Ceramic	SSC Sensor Chain Stainless Steel Capillary
Description	Compact Interrogator	Compact Interrogator	Bare Fiber, SM800 P=Polyimide-coated A=Acrylate-coated	Bare Fiber mounted in PEEK tubing	Bare Fiber mounted in Silica or Alumina Ceramic Capillary Tube	Bare Fiber mounted in Stainless Steel Capillary Tube
No. of Channels	1, Wideband (W)	4, Wideband (W)	1	1	1	1
Measurement	Temperature, °C Strain, µe	Temperature, °C Strain, µe	Temperature and Strain	Temperature and Strain	Temperature	Temperature
Precision	0.1-1°C or 1-10µe depending on sample rate	0.1-1°C or 1-10µe depending on sample rate	Sensor Configurations: A-n-W-GL-FI P-n-W-GL-FI UHS-n-W-GL-FI	Sensor Configurations: A-n-W-GL-PK P-n-W-GL-PK	Sensor Configurations: P-n-W-GL-SI UHT-n-W-GL-SI UHT-n-W-GL-AC	Sensor Configurations: P-n-W-SST-SSC UHT-n-W-SST-SSC
# of FBGs per Sensor (n)	1-30	1-30	1-30	1-30	1-30	1-30
Sample Rate/channel	1-100Hz	1-100Hz	Min FBG spacing=2mm Max length=500m	Min FBG spacing=2mm Max cap length=10m	Min FBG spacing=2mm Max cap length, SI=2m, AC=1m	Min FBG spacing=2mm Max cap length=3m
Operating Temperature	0°C to +60°C	0°C to +60°C	Capillary Section: For A: -40°C to +80°C For P: -40°C to +300°C For UHS: -250°C to +300°C	Capillary Section: For A: -40°C to +80°C For P: -40°C to +300°C	Capillary Section: For P: -40°C to +300°C For UHT: -250°C to +800°C	Capillary Section: For P: -40°C to +300°C For UHT: -250°C to +800°C
Applications	Laboratory or Embedded OEM	Laboratory or Embedded OEM	General purpose. Supports temperature and strain measurements. FBGs must be strain-relieved for temp.	Flexible tubing provides protection of internal FBGs, as required by specific applications.	Provides strain-relieved, semi-rigid temperature probe for measurements to +800°C.	Provides strain-relieved, rigid temperature probe, well-suited for high temp measurements to +800°C.
Electrical Interface	UART and microUSB	UART and microUSB	---	---	---	---
Optical Interface	FC-APC	FC-APC	FC-APC	FC-APC	FC-APC	FC-APC
Power Supply	+5VDC or USB	+5VDC or USB	---	---	---	---
STOCK PRODUCTS	FBGX100	FBGX400	Available for initial engineering evaluation: FBG-MR0050, 1-FBG FBG-MR0010, 10-FBG Or ordered per customer-specified configuration	Ordered per customer-specified configuration	Ordered per customer-specified configuration	Ordered per customer-specified configuration

P=Polyimide-Coated Fiber, A=Acrylate-Coated Fiber (rated -40C to +80C)
UHS=Ultra High Strength, Pure Silica Core Fiber with No Coating
UHT= Ultra High Strength, Pure Silica Core Fiber with Polyimide Coating

98-FISN-06-A

QR Code to FBGs

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VENTURA, CA 93003 USA

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sales@micronor.comhttps:

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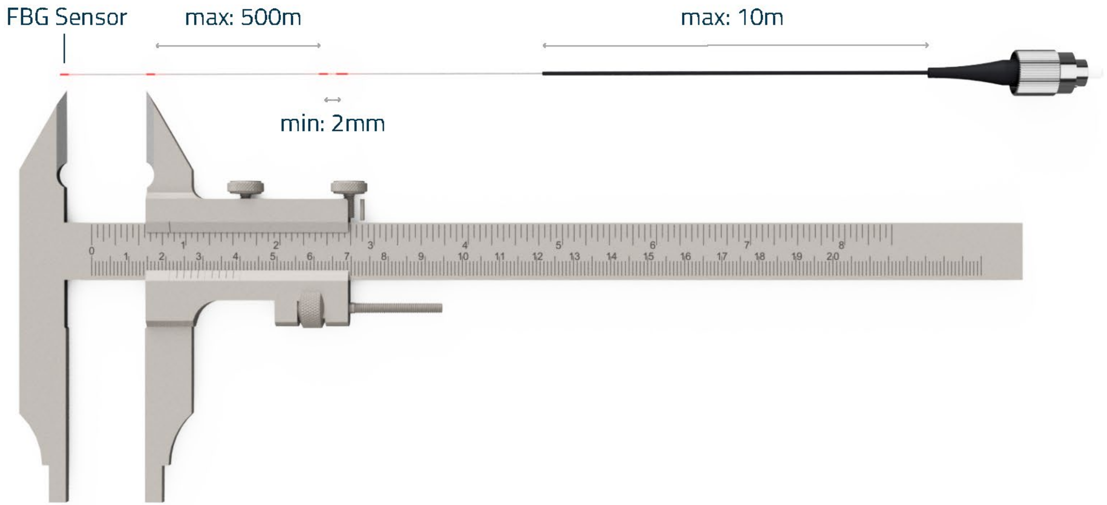
How To Specify a FiSens FBG Sensor Chain

Up to 30 FBG at arbitrary Positions

Position Tolerance: 0,3%/m



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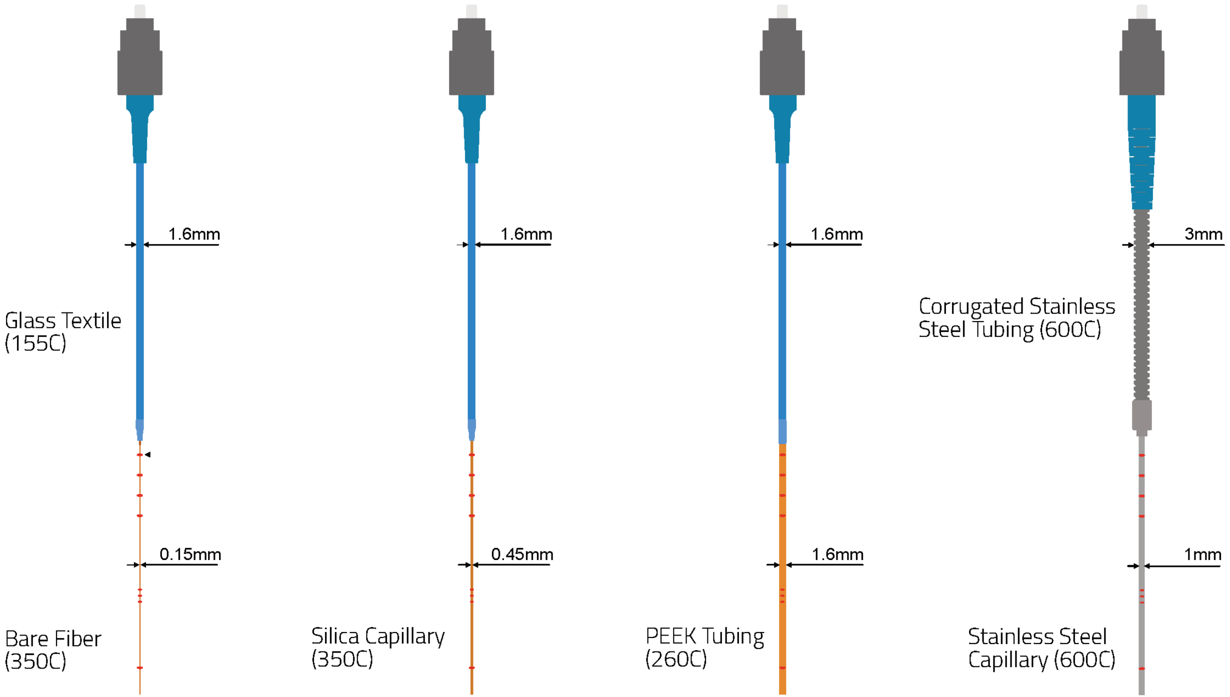
Off-The-Shelf FBG Packaging Options



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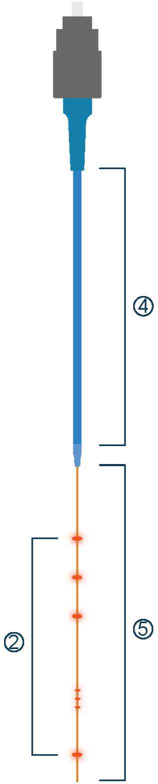
How To Specify an FBG Sensor Chain

Step 1



Ⓐ FBG Array Part Number

① Sensor Type
P - Polyimide
A - Acrylate
UHS - *Ultra-High Strength*
UHT - *Ultra-High Temp*

③ Spectral Range
N - *Narrow [808-865]*
W - *Wide [808-880]*
C - *Custom*

⑤ Sensor Capillary
FI - *Bare Fiber*
PK - *PEEK Tubing*
SSC - *SS Capillary*
SI - *Silica Capillary*
HY - Hytrel Tubing
AC - *Alumina Ceramic*

P - 5 - N - GL - FI

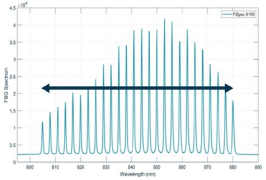
② FBG Quantity
1 - 1 FBG
2 - *2 FBGs*
...
30 - *30 FBGs*

④ Lead-in Protection
GL - Glass Textile
SST - SS Flexible Tube
HY - Hytrel Buffer
LSZ - Standard Telecom

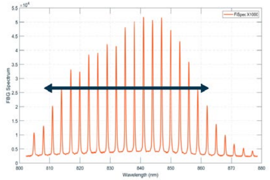
① Sensor Type

	Fiber	Application	Operating Temperature	Capillary Options (5)
P	SM800, Polyimide Coating	Strain, Temperature	-250...+300C	FI, PK, SSC, SI, HY
A	SM800, Acrylate Coating	Temperature	-40...+80C	FI, HY, PK
UHS	Pure Silica Core, Polyimide Coating	Strain	-250...+300C	FI
UHT	Pure Silica Core, No Coating	Temperature	-250...+800C	SSC, SI, AC

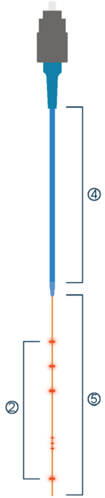
③ Wide Spectral Configuration [for X100-X400]



Narrow Spectral Configuration [for X1000-X4000]



How To Specify an FBG Sensor Chain



Ⓐ FBG Array Part Number

① Sensor Type
P - Polyimide
A - Acrylate
UHS - *Ultra-High Strength*
UHT - *Ultra-High Temp*

③ Spectral Range
N - *Narrow [808-865]*
W - *Wide [808-880]*
C - *Custom*

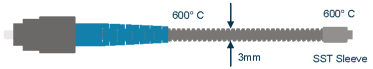
⑤ Sensor Capillary
FI - *Bare Fiber*
PK - *PEEK Tubing*
SSC - *SS Capillary*
SI - *Silica Capillary*
HY - Hytrel Tubing
AC - *Alumina Ceramic*

P - 5 - N - GL - FI

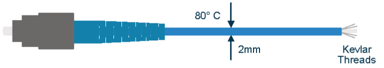
② FBG Quantity
1 - 1 FBG
2 - *2 FBGs*
...
30 - *30 FBGs*

④ Lead-in Protection
GL - Glass Textile
SST - SS Flexible Tube
HY - Hytrel Buffer
LSZ - Standard Telecom

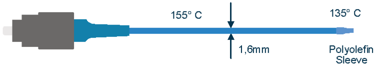
④ SST - Stainless Steel (1.4301) Corrugated Tube



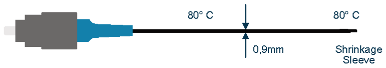
LSZ - Low Smoke Zero Halogen



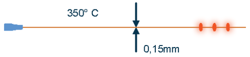
GL - Glass Textile



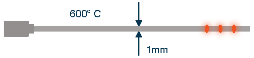
HY - Hytrel Buffer



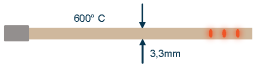
⑤ FI - Bare Fiber with Polyimide Coating



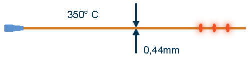
SSC - Stainless Steel (1.4301) Capillary



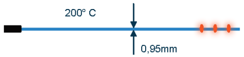
AC - Alumina Ceramic



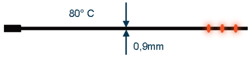
SI - Silica Capillary



PK - PEEK Tubing

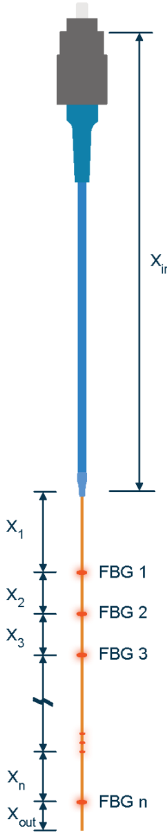


HY - Hytrel Tubing

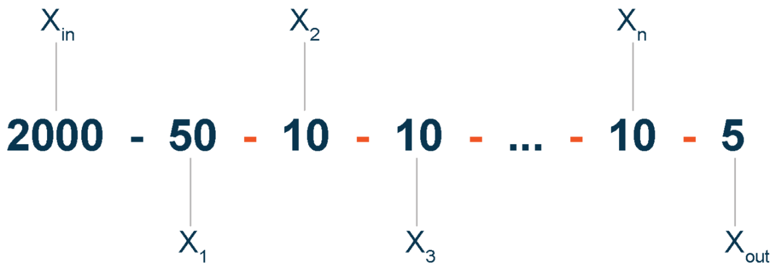


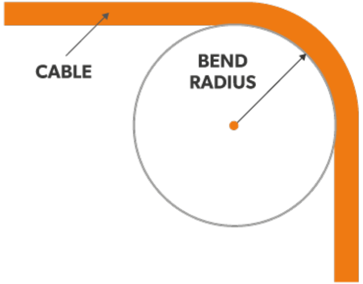
How To Specify an FBG Sensor Chain

Step 2



Ⓑ FBG Array Distance Code





Length/Bending Limitations

	4. Lead-in Protection				5. Sensor Capilary				
	SST	LSZ	GL	HY	FI	SSC	SI	PK	AC
Crit. Bending Radius	15mm	10mm	5mm	5mm	5mm	100mm	20mm	40mm	-
Max length	10m	10m	5m	5m	500m	3m	2m	10m	1m
Min length	0,5m	0,5m	200mm	20mm	20mm	100mm	50mm	50mm	100mm

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How To Specify an FBG Sensor Chain

Step 3 (Optional)

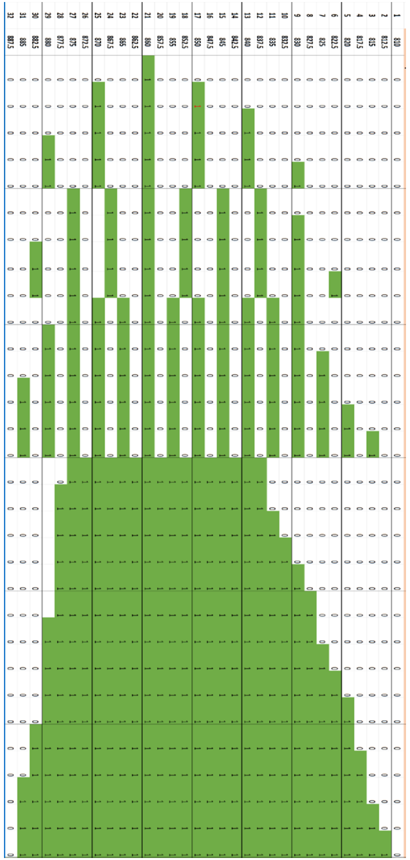
Ⓒ Customized FBG Wavelength Code (only if custom sensor type: “C“)

WL1	WL2	WL3		WLn
810	**840**	**845**	**...**	**870**

810 - 840 - 845 - ... - 870

CWL Tolerance: 0,15nm

CWL Range: 800-900nm



Performance Comparison of Key Thermometry Technologies

Typical Characteristics	K-Type Thermocouple	GaAs	FBGs
Measurement Range	-270°C to 1260°C	-200°C to +300°C	8.65 pm/°C -250°C to +800°C ±208°C for 10 FBGs ±92.5°C for 30 FBGs
No. of Measuring Points per Sensor	1	1	1-30
Accuracy	±2.2°C	±0.2°C (1σ)	~1-2°C
Resolution	0.1°C	0.1°C	0.1°C – 0.5°C
Update Rate	0.1 Hz	1-ch = 4 Hz 4-ch = 1 Hz	1-100 Hz (FBGX100) 1-2000 Hz (FBGX1000)
Max Distance	50m	2000m	500m
Wire Used	Metallic	Multimode Glass Fiber 200/220	Single Mode SM800P 5.6/125
Ease of Integration	Plug-and-play	Plug-and-play	Requires Hardware and Software Integration

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Application Comparison of Key Thermometry Technologies

Environment	K-Type Thermocouple	GaAs	FBGs
Benign, Short Distance <30m	✓	✓	✓
Benign, Long Distance	✗	✓	● FiSpec < 500m
High Temperature > 300°C	✓	✗	✓
Low Temperature < -40°C	✗	✓	✓
EMI/RFI	✗	✓	✓
Magnetic Fields	✗	● (Requires offset factor for >1 Tesla)	✓
High Voltage	✗	✓	✓
RF Fields	✗	✓	✓
RF or Conductive Heating	✗	✓	✓
Microwave Oven	✗	✓	✓
Radiation (Nuclear)	● Requires Radiation Compensation	✓	✓ Use UHT Silica Core Fiber

✓ Recommended

● Provisional

✗ Not Recommended

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Performance Comparison of Key Strain Sensors Technologies

Typical Characteristics	Load Cell	Thin Film Strain Gauge	Optical Strain Guages (LW FBGs)	FBGs (SW FBGs)
# of Points per Sensor	1	1	Single point (1550nm)	1-30, min 2mm spacing (850nm)
Measurement Range	Measure force, 0-10 kN	±500 $\mu\varepsilon$	**1.4 pm/$\mu\varepsilon$** ±2,500 $\mu\varepsilon$	**0.7 pm/$\mu\varepsilon$** ±3,000 $\mu\varepsilon$ for 10 FBGs ±2,000 $\mu\varepsilon$ for 30 FBGs
Operating Temperature Range	-40°C to +140°C	-40°C to +85°C	-40°C to +85°C	-250°C to +300°C
-3dB Frequency Response or Digital Sample Rate	1-10kHz	1-10kHz	1-100kHz	FBGX100 1-100Hz FBGX1000 1-2000Hz
Output	Analog	Analog	Digital	Digital
Max Distance	<10m	<10m	>>1000m	500m
Wire Used	Metallic (2-4 Wires)	Metallic (2-4 Wires)	Single Mode Fiber SMF28	Single Mode Fiber SM800-5.6/125
Ease of Integration	Plug-and-play	Plug-and-play	Somewhat Plug-and-Play	Requires Hardware and Software Integration

Application Comparison of Key Strain Sensor Technologies

Environment	Strain Gauges Load Cells	FBGs (All Types)
Benign, Short Distance <30m	✓	✓
Benign, Long Distance	✗	✓ FiSpec < 500m, LW<< 1km
High Temperature > 300°C	✓	✓
Low Temperature < -40°C	✗	✓
EMI/RFI	✗	✓
Magnetic Fields	✗	✓
High Voltage	✗	✓
RF Fields	✗	✓
RF or Conductive Heating	✗	✓
Radiation (Nuclear)	● Requires Radiation Compensation	✓ Use UHS Silica Core Fiber
Temperature Compensation Required	✓	✓

✓ Recommended

● Provisional

✗ Not Recommended

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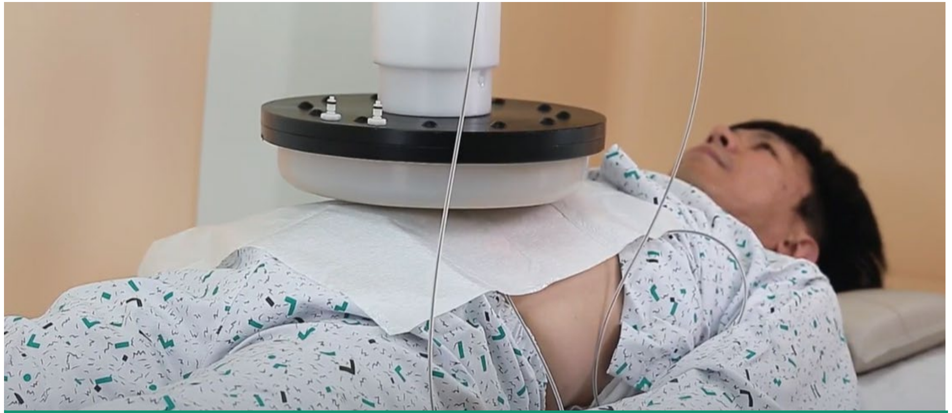
Case Study #1: Medical – RF Radiotherapy

FO Attributes



Patient Monitoring during hyperthermia cancer treatment

CHALLENGE

Monitor patient skin temperature during High-RF Field hyperthermia cancer treatment. Requires immunity to RF fields. Measurement range is 0-80°C (23°F to 176°F).

SOLUTION

TS5 temperature probe is taped to patient's skin during hyperthermia (RF heating) cancer treatment

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Case Study #2: Medical – MRI

FO Attributes

CHALLENGE

Monitor patient skin temperature, ambient temperature as well as internal MRI hardware. Magnetic field strength up to 9 Tesla (T). There is also emerging cancer imaging technology requiring sensing of nanomagnetic fields emitted by targeted magnetic nanoparticles which tag and detect cancer.

SOLUTION

GaAs TS5 used for patient monitoring. TS2 used to monitor magnetic coils and internal electronics. Non-metallic design is both immune and invisible to electrical and resistant to magnetic fields.

Case Study #3: Biomedical Research-Nanoparticles

FO Attributes

CHALLENGE

Magnetic nanoparticles are heated with induction to selectively ablate tumor cells, powers from 1kW to 10kW, frequencies from 150kHz to 400 kHz. This non-contact selective heating only elevates the temperature of the material or tissue with embedded magnetic nanoparticles. Requires RF immune temperature sensor to monitor actual temperature.

SOLUTION

Ambrell EASYHEAT® System is a compact induction heating system for the lab which offers Weidmann TS3 GaAs sensor (both non-metallic and RF-immune) for both temperature indication and closed loop control of the customer’s process.

Case Study #4: Food Processing - Microwaves

FO Attributes

Commercial Microwave Oven and Industrial Microwave Conveyor Drying Machine

CHALLENGE

Measuring temperature of food and similar samples while being heated in Microwave Oven. Food can absorb microwaves, but metal can only reflect. This can cause a dangerous arcing condition between the metal object (conventional temperature probe) and the metal walls of the microwave oven. Monitor temperatures to 200°C.

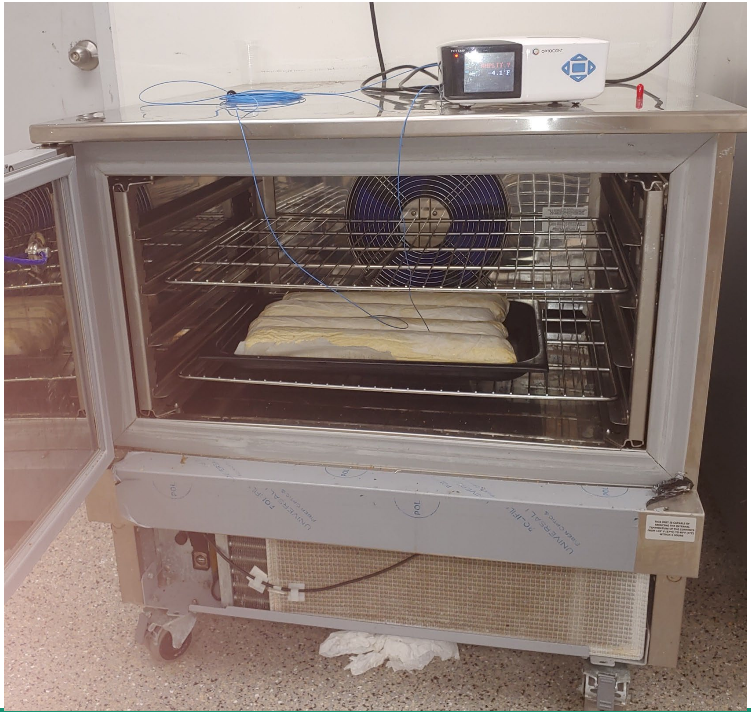
SOLUTION

Fiber optic temperature sensors are both non-metallic and immune to microwaves.

Compared with traditional natural defrost thawing, flooding or water thawing, microwave defrosting has advantages of short time, uniform internal/external heating, kills bacteria, and no loss of nutritional components.

Gefilte Fish: Using Microwave Ovens

FO Attributes



Microwave Food Processing using TS3 GaAs Temperature Probe

CHALLENGE

Develop optimized process for meat thawing as well as production of partially cooked food product.

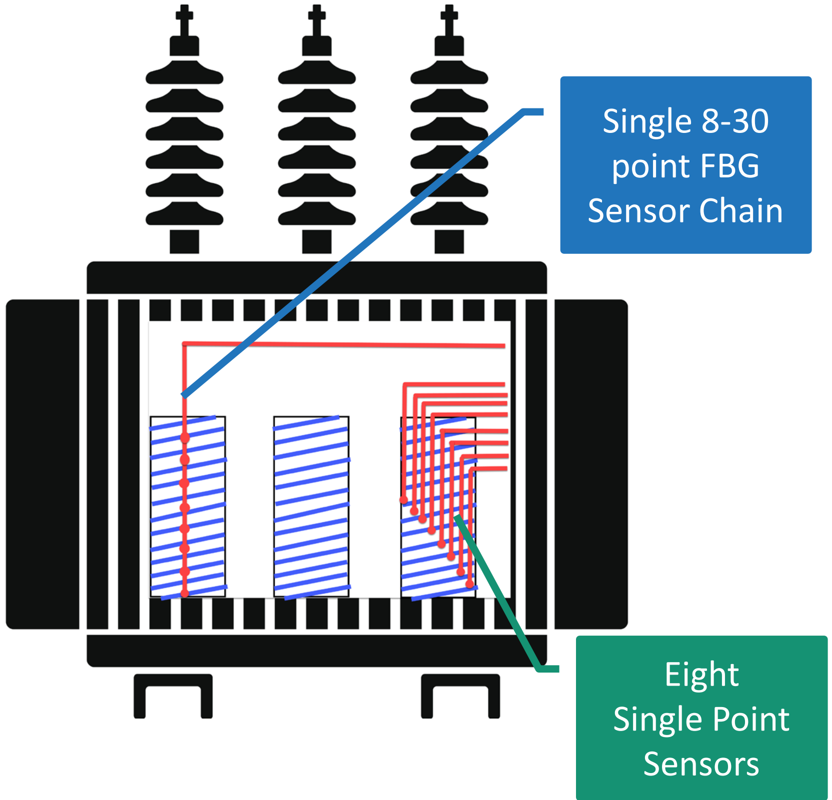
SOLUTION

A&B Famous Gefilte Fish uses multichannel Bench Top FOTEMP signal conditioner together with TS3 series GaAs temperature probes.

A&B developed a proprietary microwave oven-based process for raw fish thawing as well as production of their partially cooked frozen gefilte fish product. For the latter, a microwave oven process was developed that precisely cooks and cools the product without rendering the proteins fully cooked.

Case Study #5: Energy -Health Monitoring of Transformer Hotspots & Bus Bars

FO Attributes



CHALLENGE

Safe monitoring of generation and distribution transformers with internal potentials range from 15 kV to 10,000 kVA.

SOLUTION

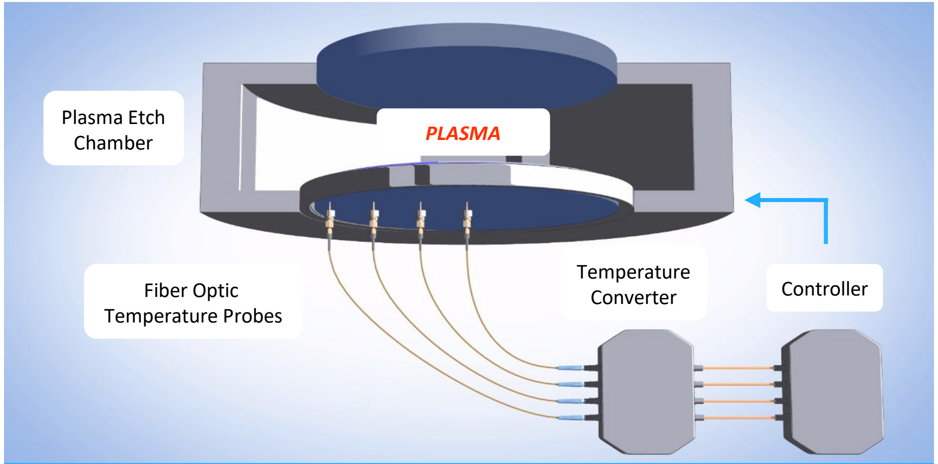
Fiber optic temperature sensors provide inherent immunity to high voltages.

Real-time Hotspot Temperature Sensing monitors health of the transformer, improves reliability, and prevents unscheduled system failures and outages.

Current system uses 24x TS2 GaAs Temperature Probes. Future system simplifies system using only 3x FBG probes providing greater fidelity = up to 90 monitoring points.

Case Study #6: Semiconductor Equipment Mfg

FO Attributes



Application Diagram: Temperature Sensing Inside Etch Chamber

CHALLENGE

Precisely measuring temperature in Plasma Etch Vacuum Chamber during wafer etching. Monitoring and controlling temperature improves wafer yields and lowers costs. Requires immunity to RF and plasma fields.

CURENT SOLUTION

Current processes use single point fiber optic temperature probes, based on GaAs, Phosphoresence or Fluorescence. Working temperatures to 450°C and absolute accuracies down to ±0.2°C.

GaAs is the only technology that is absolute, based on intrinsic properties of GaAs. Phosphorescent and Fluorescent probes on based on well-characterized phosphor compounds which require calibration/based

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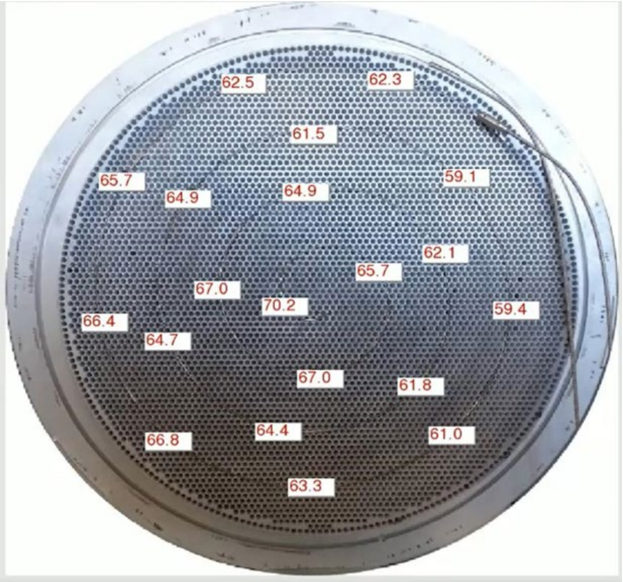
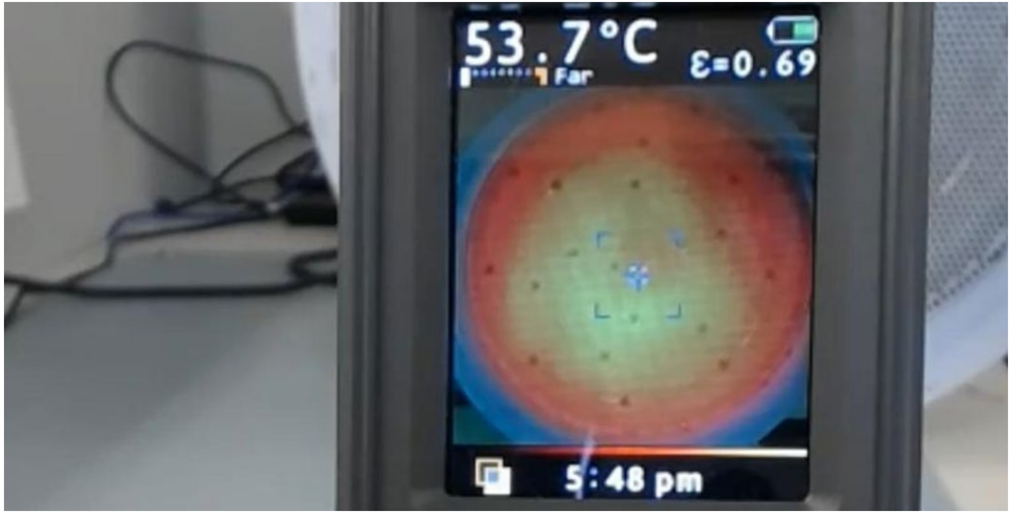
EMERGING SOLUTION
Multipoint FBGs Promise More Comprehensive Temperature Feedback in Semi Device Manufacturing Processes

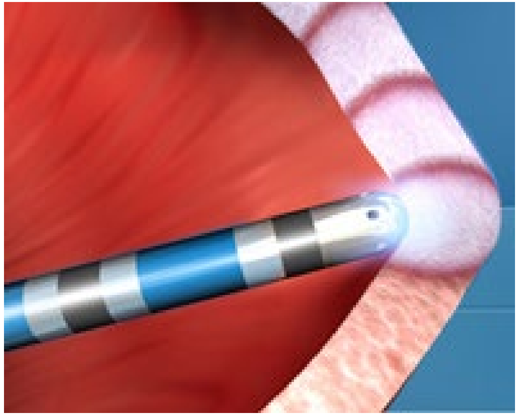
FBG Demo on Plasma Shower Head

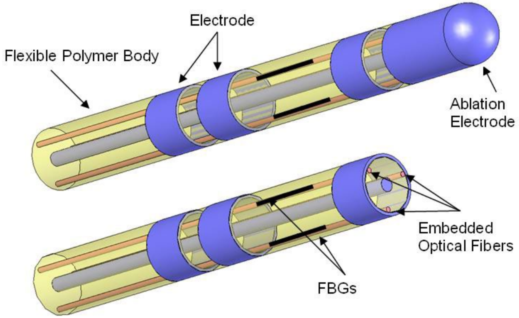




Case Study #7: Integrated Strain & Temperature sensing in RF Ablation Catheter

FO Attributes





CHALLENGE

RF ablation cather is directed through the body and positioned to burn off tumors. Physicians require real-time, objective measure of contact force during treatment of cardac arrhythmias or tumors.

SOLUTION

A single FBG can be used to monitor contact force during RF ablation procedure. Multiple FBG sensor chains can be used when high force sensing fidelity is required. FBGs in same sensor chain monitors temperature during RF ablation procedure so not to overheat and damage surrounding tissue.

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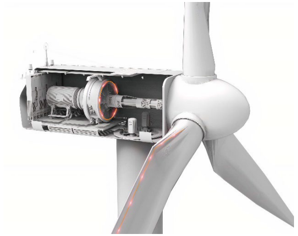
Case Study #8: Additional Embedded FBG Temp and Strain Monitoring Applications for Health & Safety

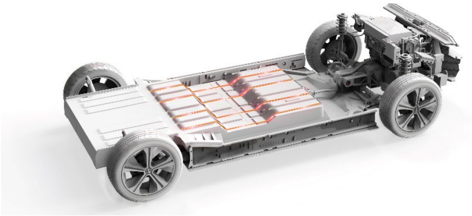
FO Attributes

Aircraft Structural
Health Monitoring

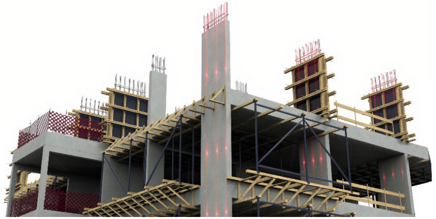
Infrastructure Health
and Safety Monitoring



Wind Turbine Blade and
Generator Health Monitoring



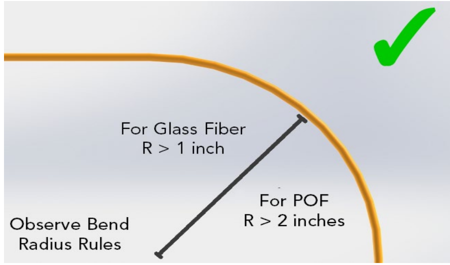
Battery
Health Monitoring

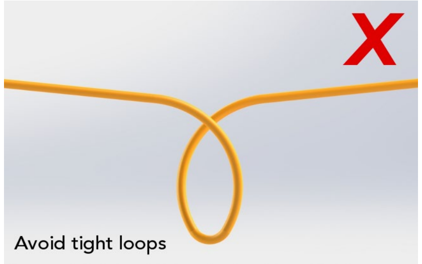


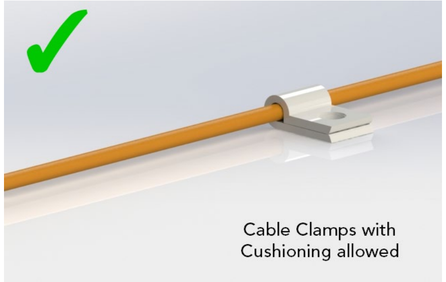
Civil Structure Health
and Safety Monitoring

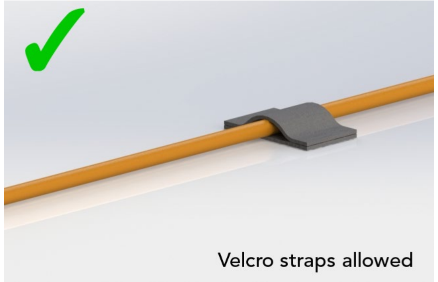
Load and Balance
Safety Monitoring

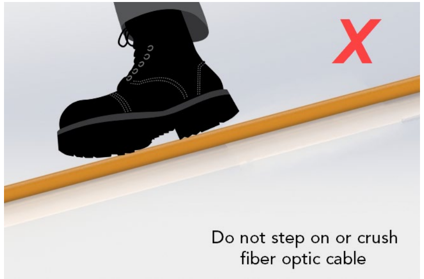
Basic Fiber Do’s and Don’ts

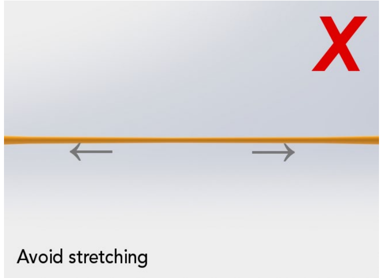












Summary

- MYTH: Fiber optic sensors are not fragile, glass things. FO is very robust and reliable.
- Fiber optic temperature sensors solve many environmental and packaging challenges in the unique operating conditions of many medical and industrial applications – beyond the capabilities of conventional electronics-based sensors, i.e. where immunity to interference, e-fields, magnetic fields, rf fields, or long distances is required.
- Fiber optic temperature sensors enhance applications where thermocouples are incompatible and offer real-time monitoring solution improving the operation and reliability of the overall system, i.e. RF Ablation, MRI, Transformer Hot Spot Monitoring, etc.
- Fiber Bragg Grating sensors offer both temperature and strain monitoring in a single fiber sensor for the most compact sensor solution. Multipoint sensor chains provide high fidelity not possible with other sensor technologies.
- Reach out for a fiber optic temperature sensor solution in your next project.

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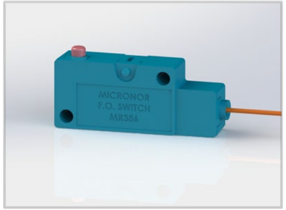
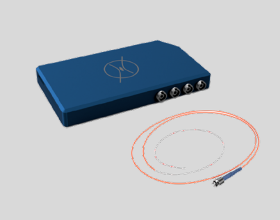
Fiber Optic and Electromechanical Sensors





Fiber Optics

- ❑ Absolute and Incremental Encoders
- ❑ Emergency Stop
- ❑ Microswitch
- ❑ Accelerometer (Micronor AG)
- ❑ Temperature (Weidmann FOTEMP GaAs sensors)
- ❑ Temperature and Strain (FiSens FBGs)

MICRONOR® optical sensors

OPTOCON® OPTICAL SENSORS AND SYSTEMS by WEIDMANN

FiSens

Electromechanical

- ❑ Position Transducers/Feedback Units
- ❑ Rotary Limit Switches
- ❑ Optical/Magnetic Encoders
- ❑ Resolvers
- ❑ Cam Timers/Motorized Potentiometers
- ❑ HMI – Handheld Pendants and MPGs

MICRONOR® mechanical products

Questions?

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