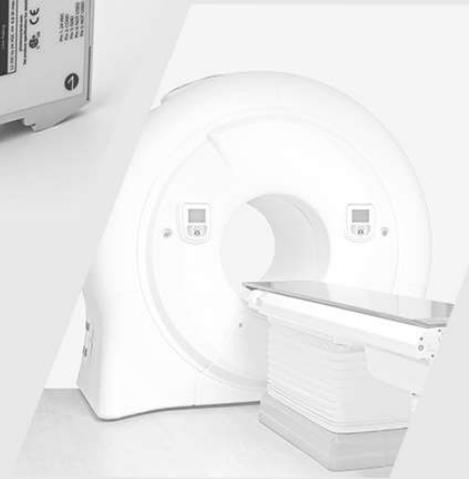


Fiber Optic Temperature Sensing in Harsh Environments Using Phosphor Thermometry

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1. Abstract

Fiber optic temperature sensors are critical for harsh environments where traditional electric sensors cannot perform reliably. Temperature monitoring is vital to many processes, as extreme temperatures can damage manufacturing and testing capabilities. This white paper will specifically describe phosphor thermometry, a robust technology that provides accurate and reliable temperature sensing, ideal for demanding applications.

2. Background

2.1. Fiber Optic Sensors

Innovation within the fiber optic industry has led to not only improved light sources and cabling, but also the development of fiber optic sensors. A fiber optic sensor is entirely controlled by light and does not include any electrical components. Typically, a fiber optic sensor is “interrogated” using a quantity of light, and the sensor alters the properties of this light signal in proportion to the physical quantity being measured. The interrogator translates the received optical signals back into electronic quantities in either analog or digital form and serves as the interface to the attached control equipment. Now, sensors for temperature, strain, position, speed, angle, vibration and sound have all been realized and are offered commercially.

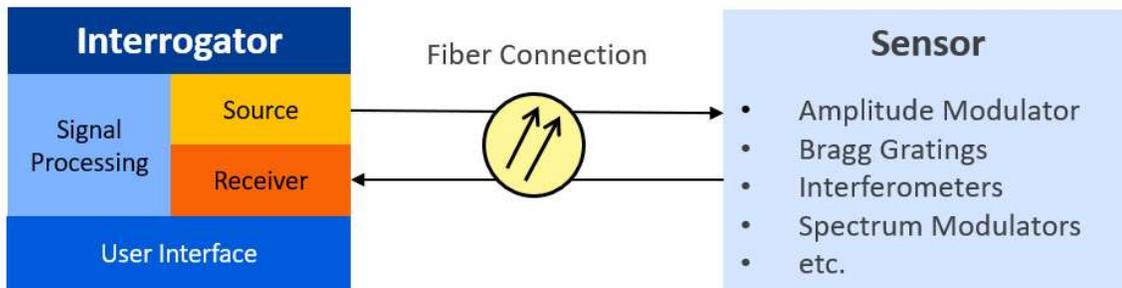


Figure 1. Fiber Optic Sensor System

2.2. Temperature Sensors

With regards to temperature sensors, there are now a wide variety of systems available today, including electronic thermometers, infrared pyrometers and luminescent-based probes. While electronic thermometers such as thermocouples and thermistors can offer accurate temperature sensing, their dependence on metallic leads and components is not suitable in the presence of electromagnetic interference (EMI), high magnetic fields and high voltage environments. On the other hand, infrared sensors are non-contact sensors that use infrared energy to determine temperature. The downside of infrared pyrometry is that these sensors can pick up energy from the surroundings and provide an inaccurate measurement. Finally, luminescent-based probes determine temperature through the light emission properties of different substances. Since the light emission is temperature dependent, luminescent-based sensors have become the go-to in fiber optic temperature sensing.

2.3. Why Fiber Optics?

Fiber optic sensors are not meant to replace electronic based sensors. Rather, they are meant to enable new technologies in situations where electrical sensors are not suitable. In fact, fiber optic sensors can even provide several advantages in the rigid environments where electrical sensors are infeasible.

To begin, fiber optic sensors and cabling do not contain any electrical components. As a result, they are immune to the effects of EMI, high voltage, lightning and radiation. This electrical isolation makes fiber optics inherently safe to use, meaning there is no danger of sparking or overheating, even if a probe or cable breaks. Sensors can even be deployed within an MRI bore as they are not only unaffected by the extreme magnetic fields, but they also remain invisible to the imaging process, provided they are built using non-ferrous and non-conducting materials. These features can significantly reduce noise within the system, providing more accurate measurements and greater reliability as opposed to their electrical counterparts.

In addition, fiber optics can provide further advantages for specific applications. For example, ultra-small sensor probes (as small as 0.5mm diameter) can be used as a small form factor solution where space is of the essence. Meanwhile, fiber optic cabling can offer greater bandwidth, faster speeds and longer distance communication when compared to similar copper cables. Lastly, copper wire transmission can generate sparks, causing shortages and even fire. With fiber optics, the chance of electrical fire is eliminated, fundamentally improving safety.

2.4. Industries

Some popular industries that use fiber optic sensors include, but are not limited to:

- Medical
- Military and Government
- Oil & Gas
- Civil Infrastructure
- Industrial
- Power
- Telecommunications



3. Phosphorescent Thermometry

3.1. What is Phosphorescent Thermometry?

Fiber optic temperature sensors use light to transmit temperature information using a temperature sensitive material as a sensor. As the temperature changes, the sensor's properties are altered, resulting in light-based reactions such as transmission, reflection, fluorescence or absorption. The resulting optical signal is then relayed through optical fibers to an opto-electronic detection system which converts the signal into a temperature reading.

In phosphorescent thermometry, a phosphor material is coated on an optical fiber or on an object in line of sight of the optical signal. It is then excited using a light pulse. As seen in *Figure 2*, the phosphor begins in its ground state (1). It is then stimulated using photons that excite electrons to a higher energy level in the atom (2). Then, the phosphor goes through phosphorescence, a type of luminescence similar to fluorescence. The electrons relax and return to their previous state, emitting low intensity light (3). In this case, blue light is used as stimulation and red light is emitted.

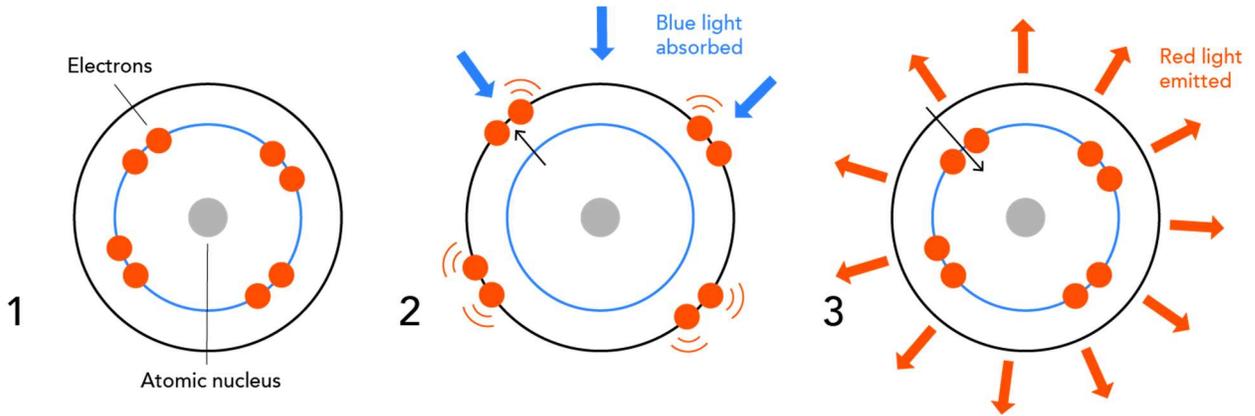


Figure 2. Phosphor Atom Excited with Blue Light, Emits Red Light as it Relaxes

As seen in *Figure 3*, the luminescence persists for a characteristic amount of time after excitation. The time required for the brightness to decay is directly related to absolute temperature, allowing the probe to infer the temperature of an object. *Section 3.2* describes this calculation in further detail.

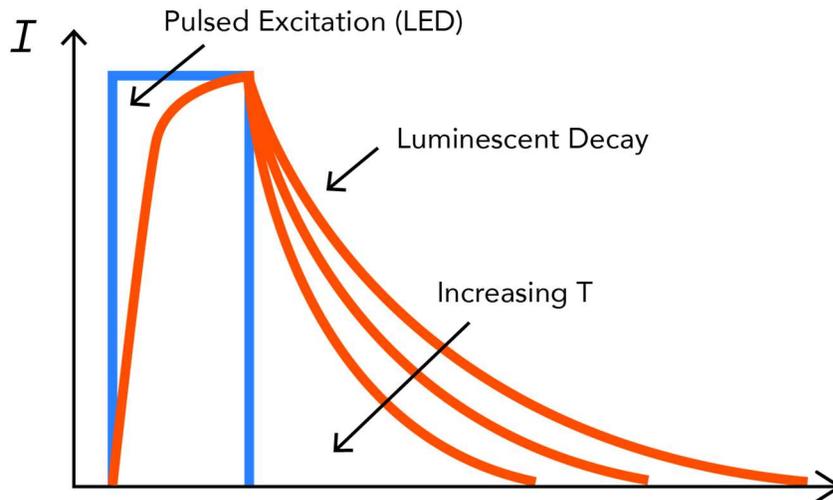


Figure 3. Phosphor Luminescence



3.2. Temperature Measurement Method

As stated above, the lifetime of the phosphor’s luminescence is temperature dependent. According to Eq. 1, the intensity decays exponentially:

$$I = I_0 e^{-t/\tau} \tag{Eq. 1}$$

Here, I_0 is the initial emission intensity, t is time and τ is the lifetime of the phosphorescence, or the amount of time it takes the intensity to decrease to $1/e$ of the initial emission intensity.

To calibrate the probe, the intensity decay can be measured at known temperatures, allowing for the calculation of the phosphorescence lifetime using the theoretical model (Eq. 1). The lifetime decreases as temperature increases, although at different rates depending on the phosphor material. On top of this, each phosphor can only cover a limited temperature range, meaning multiple phosphors are needed to measure large temperature spans. Figure 4 depicts the phosphorescence lifetimes within the temperature range of several different phosphors.

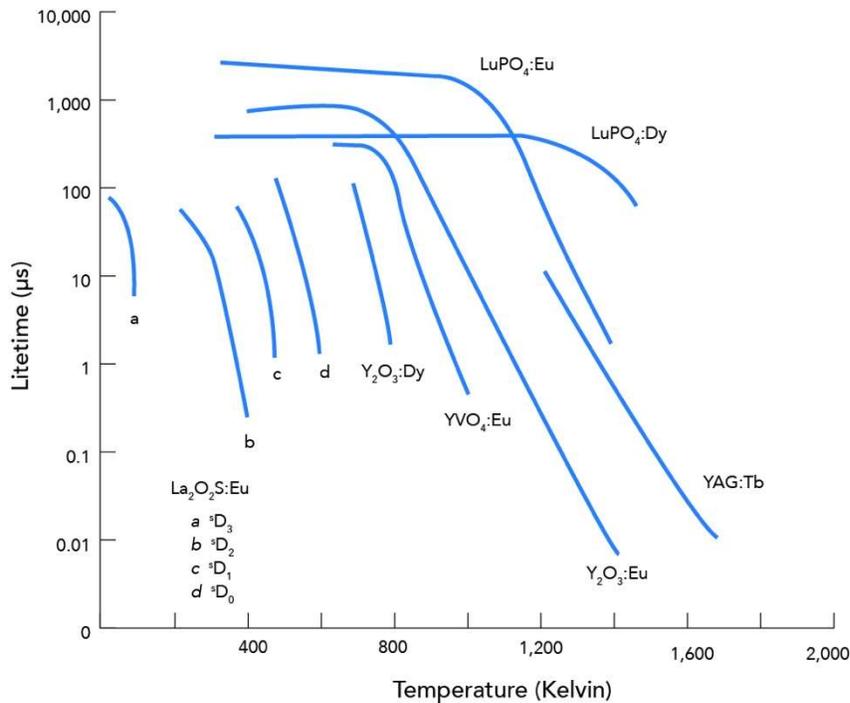


Figure 4. Phosphorescence Lifetime vs. Temperature for Different Phosphors

Once the phosphorescence lifetime spectrum for a specific phosphor is known, it can be used as a temperature sensor. Figure 5 shows the intensity of emitted light for the phosphor La₂O₂S:Eu at 65°F and 75°F. As expected, the lifetime becomes shorter (i.e., intensity decays faster) at higher temperatures. The error in temperature using this model is ideally under 1%.



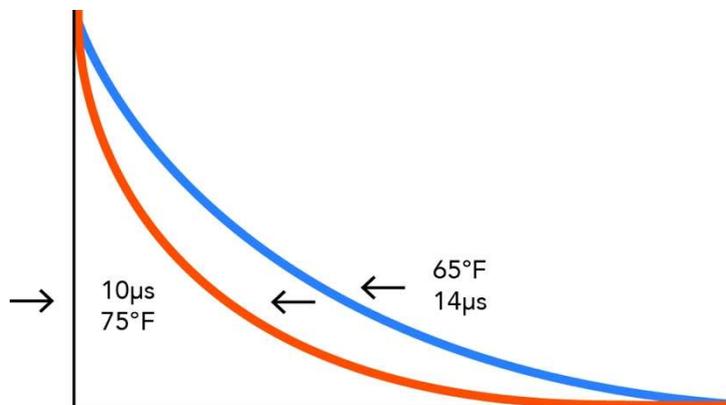


Figure 5. Phosphor Decay at 65 and 75 F (La2O2S:Eu)

3.3. Thermometry System

Figure 6 below depicts the entire thermometry system in more detail. Starting in the converter, blue light is transmitted using a light emitting diode (LED). The blue light travels through fiber optic cabling until it reaches the phosphor probe, stimulating a temperature-based response. The emitted red light travels back through the cabling where it is directed to a photodetector inside the converter. Here, the photodetector translates the photon energy of the red light into a corresponding electrical signal. Finally, the converter processes the decay time of the electrical signal and determines the absolute temperature at the tip of probe.

Product specifications for the converter and available probes can be found in Section 5.

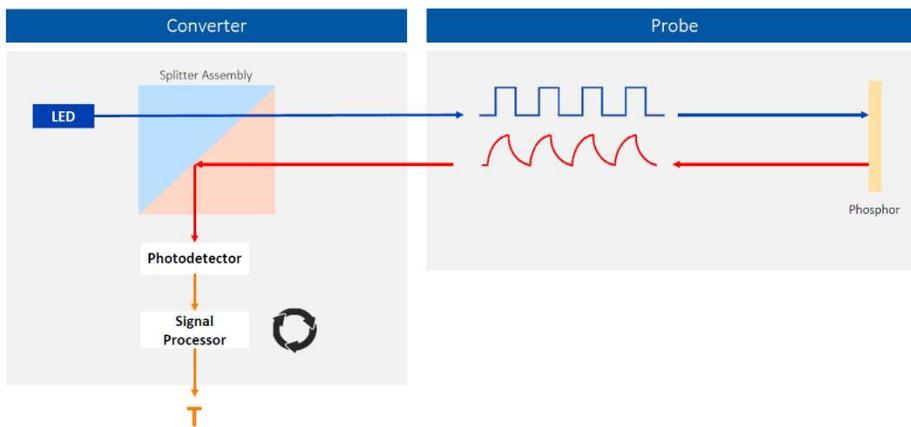


Figure 6. Thermometry System Diagram



3.4. Probe Types

When it comes to selecting a probe for a certain application, there are three main types: immersion, contact and remote. Immersion probes are the most general-purpose category of sensors in which the thermal sensing element is located at the tip of the probe. The probe is then inserted into the media or affixed mechanically to a surface. The main advantage of immersion probes is their ease of insertion into soft media samples, such as liquids, powders, gels, food and tissue.

Meanwhile, contact probes use spring-loaded mechanisms to optimize mechanical and thermal coupling to a surface which is especially useful when monitoring the surface temperature of flat objects, tools and plates that are stationary or robotically positioned. The spring action of the contact probes provide an advantage as they can be used in both fixed and dynamic (i.e., vibrating) applications.

Finally, whereas immersion and contact probes must be in contact with the fluid or object they are measuring, remote probes provide an alternative where the probe does not directly contact the surface being measured. The thermal sensing element is applied directly to a surface or mounted nearby, while the fiber optics are located at a defined gap in the range of 2-20mm depending on the application.

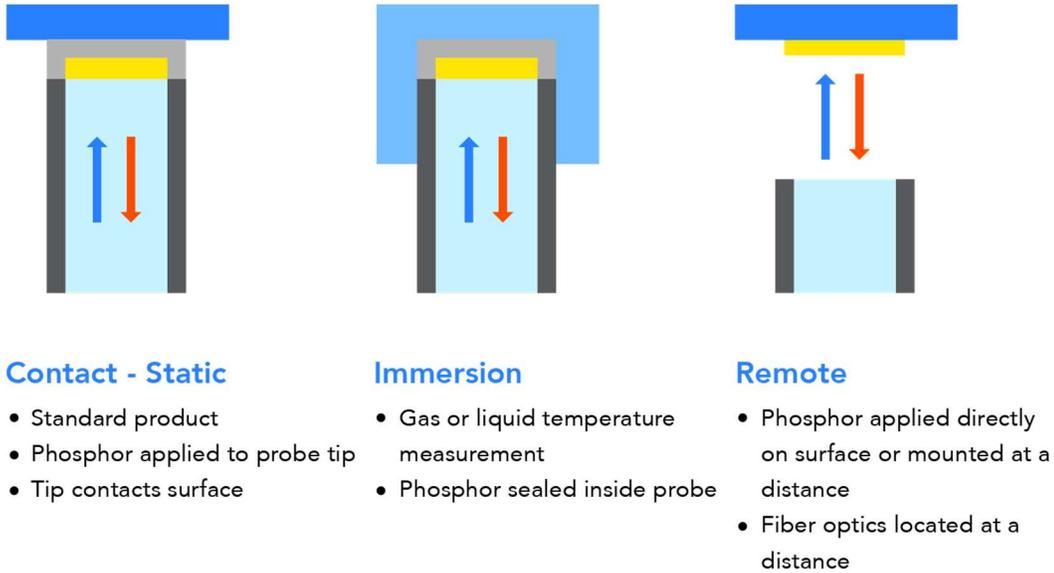


Figure 7. Probe Types

4. Temperature Sensor Technology Comparison

4.1. Temperature Sensor Technologies

For temperature sensing in a benign environment, K-type thermocouples typically remain the best option as they provide a low cost, high quality sensor with an extremely wide temperature range. However, where fiber optic sensors are needed, there are two main sensor types: phosphor and gallium arsenide (GaAs). Whereas phosphor sensors use phosphorescent decay to measure temperature, GaAs sensors use the wavelength dependence of the intrinsic band gap of GaAs to measure temperature. And, while thermocouples are often the cheapest solution, GaAs sensors are generally the most expensive option due to their complex electronics.

4.2. Performance Comparison

The table below describes typical performance specifications for the three temperature sensing technologies mentioned based on currently available products.

Typical Characteristics	K-Type Thermocouple	Phosphorescent	GaAs
Temperature Range	-270°C to +1260°C	-40°C to +450°C	-200°C to +300°C
Accuracy	± 2.2°C	± 0.2°C	± 0.2°C
Resolution	0.1°C	0.01°C	0.1°C
Update Rate	0.1 Hz	30 Hz	1-ch = 4 Hz 4-ch = 1 Hz
Max Distance	50 m	20-30 m	2000 m
Wire Used	Metallic	Multimode Glass Fiber or POF (depends on sensor)	Multimode Glass Fiber 200/220
Ease of Integration	Plug-and-play	Plug-and-play	Plug-and-play



4.3. Application Comparison

The table below depicts which temperature sensor is ideal for a variety of benign and harsh environments.

Environment	K-Type Thermocouple	Phosphorescent	GaAs
Benign, Short Distance <30m	✓	✗	✗
Benign, Long Distance	✗	✗	✓
High Temperature >300°C	✓	✓	✗
EMI/RFI	✗	✓	✓
Magnetic Fields	✗	✓	• <1 Tesla
High Voltage	✗	✓	✓
RF Fields/Heating	✗	✓	✓
Conductive Heating	✗	✓	✓
Microwave Oven	✗	✓	✓
Radiation (Nuclear)	• Requires Radiation Compensation	• Requires Radiation Resistant Fiber	✓

✓ - Recommended

• - Provisional

✗ - Not Recommended

Note: GaAs is only usable in magnetic fields under one Tesla because GaAs is a semiconductor whose properties change in large magnetic fields.



5. Product Overview

Micronor offers several phosphor thermometry sensors that fulfill a range of different applications. The tables below compare four sensors and provide specifications on our multichannel converter, the MC5, compatible with each sensor.

5.1. Phosphor Sensors

The table below details the specifications of four common phosphor probes.

Specifications	C150	C250	NY2	HT1
Probe Type	Contact	Contact	Immersion	Immersion
Temperature Range	-40°C to +150°C	-40°C to +250°C	-20°C to +80°C	-40°C to +200°C
Accuracy	± 0.5°C	± 1.0°C	± 0.5°C	± 1.0°C
Cable Min. Bend Radius	25 mm	20 mm	10 mm	20 mm

Note: The C250 and HT1 sensors are currently under development and may not be available until mid-late 2021. As such, the specifications listed are preliminary and are subject to change.



5.2. MC5 Converter

The multichannel temperature converter is compatible with all fiber optic sensor probes and offers industry leading accuracy, repeatability and reliability for temperature monitoring applications. The converter is configurable up to five measurement channels offering cost reduction and space savings per measurement point.

Specifications	MC5
Number of Channels	1 to 5
Communication Protocol	Modbus® RTU, Analog or EtherCAT®
Digital Interface	RS-485
Analog Output	4 to 20 mA (16-bit DAC)
Measurement Range	Probe Dependent
Measurement Accuracy	Probe Dependent
Stability (2σ)	± 0.1 °C
Resolution	0.01 °C
Operating Temperature	5 °C to 60 °C
Input Power	24 VDC
Dimensions	141 mm H x 25 mm W x 100 mm D



Figure 8. MC5 Converter

6. Applications

Fiber optic thermometry devices provide solutions for numerous applications where the environment is too stringent for traditional sensors. Below are three examples where fiber optics enable new sensing capabilities.

6.1. Semiconductor Equipment Manufacturing

During semiconductor equipment manufacturing, the temperature must be precisely controlled during wafer etching to improve wafer yields and lower costs. On top of this, the temperature sensor must be immune to RF and plasma fields.

Now, based on FluoTemp™ phosphorescent technology, customer specific, spring-loaded contact probes can be developed with working temperatures up to 450°C and absolute accuracies down to $\pm 0.5^\circ\text{C}$.

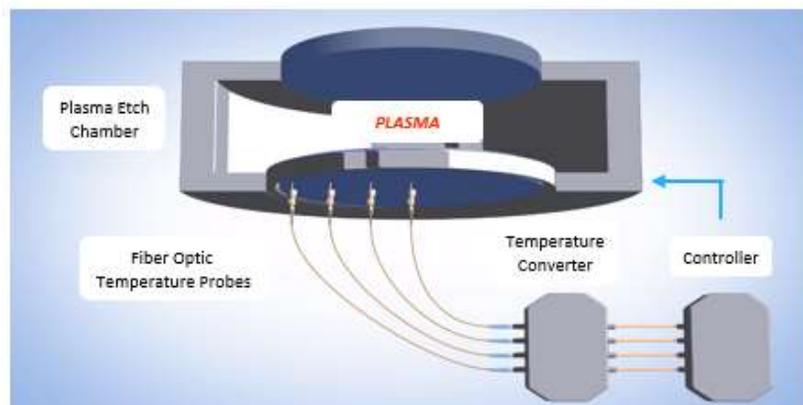


Figure 9. Temperature Sensing Inside Plasma Etch Chamber

6.2. Medical – MRI

Within MRI bores, monitoring the patient's skin temperature, the ambient temperature and the internal MRI hardware can be difficult with magnetic fields up to 9 Tesla (T). Additionally, there is emerging cancer imaging technologies that require sensing nanomagnetic fields emitted by targeted magnetic nanoparticles with tag and detect cancer.

The NY2 FluoTemp™ immersion probe is a perfect solution here, with a non-metallic design that is both immune and invisible to magnetic fields.



Figure 10. Medical MRI Environment

6.3. Power – Bus Bar Monitoring

In electric power distribution, a bus bar is used for local high current power distribution. As such, there are extremely high voltages (up to 1500 V) that can make safe temperature monitoring difficult.

Discrete fiber optic temperature sensors can be coupled to each bus bar for early hotspot detection while remaining unaffected by voltage spikes.



Figure 11. Probes Mounted on Bus Bars for Monitoring

7. Conclusion

Temperature sensing is essential in a wide range of applications. However, when the application involves an environment subject to detrimental factors such as EMI, RFI, high voltage or radiation, traditional electric thermometry sensors are insufficient. Instead, fiber optic temperature sensing using phosphor thermometry provides an alternative without sacrificing accuracy, resolution or durability.

References

EtherCAT® is a registered trademark of Beckhoff Automation GmbH.

Modbus® is a registered trademark of Schneider Electric USA, Inc.

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Micronor LLC

Micronor was founded 2003 in Newbury Park, California. The founders accurately predicted the need for fiber optic sensors which provide immunity from lightning, EMI/RFI, radiation and magnetic fields. Based on an innovative and patented technology, using wavelength as the information carrier, the first product introduced to the market were incremental encoders. These products are used in the transportation, mining, oil & gas industries for position sensing and controlling the speed of VFD drives.

Fast forward to 2020. Micronor has been acquired by Photon Control, a leading manufacturer of fiber optic temperature and position sensors. Together, they offer an unmatched source for fiber optic and electromechanical sensor solutions.

