multicore

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Multicore Fiber Based Temperature Sensor: A New Advancement in Optical Sensing

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Optical Sensing. Simplified.

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INTRODUCTION

Temperature sensing is critical in various industries such as aerospace, automotive, and industrial manufacturing. Accurate and reliable temperature sensors are essential to ensure optimal performance and prevent failures. Optical sensors have emerged as a promising alternative to conventional temperature sensors due to their high sensitivity, stability, and immunity to electromagnetic interference. However, cost has negatively impacted the adoption of optical fiber-based sensing technologies.

In this paper, we present a new multicore fiber-based temperature sensor that offers the same advantages of other optical fiber-based sensors at a much lower cost.

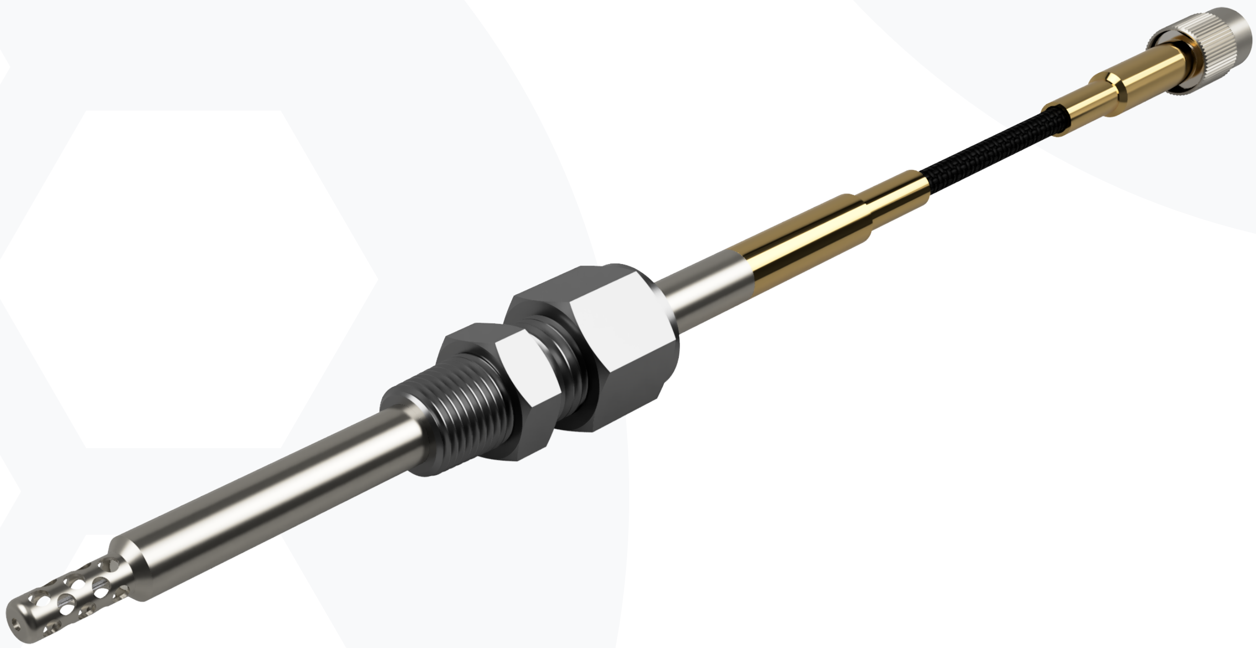

Figure 1: Automotive Packaged Temperature Sensor.

BACKGROUND

Optical fiber technology has revolutionized the field of sensing in measuring various parameters such as temperature, strain, pressure, and chemical composition. Optical fiber-based sensors offer several advantages over traditional electrical-based temperature sensing technologies like thermocouples or RTDs, including higher sensitivity, stability, and immunity to electromagnetic interference. Optical fiber temperature sensors have become particularly popular in recent years due to their high accuracy, fast response, multiplexing capability, and ability to operate in harsh environments. However, most optical fiber sensors require expensive interrogation equipment to generate accurate and stable measurements.

Fiber Bragg Gratings (FBGs) are one of the most common types and most expensive of optical-based temperature sensors. FBGs consist of a periodic structure of refractive index modulation along the length of an optical fiber. When light is launched into the fiber, a portion of it is reflected by the FBG, this reflected Bragg wavelength is sensitive to changes in temperature due to photo-elastic effects. The reflected Bragg wavelength can be measured and repeatedly tracked with high accuracy using an ultra stable laser source and an optical spectrum analyzer (OSA).

Fabry Perot Interferometers (FPIs) are another type of optical-based temperature sensor that has been adopted for use in some industrial processes. FPIs consist of two partially parallel reflecting surfaces separated by a precision length air gap cavity. When broadband light is launched into the FPI, a resonant optical cavity forms between the two mirrors, creating an interference pattern. The resulting interference pattern is sensitive responds to changes in temperature, which can be measured and tracked with high accuracy using an optical spectrum analyzer.

Fluorescence-based sensors use the change in fluorescent intensity to detect temperature. A Fluorescent material is embedded in a temperature-sensitive matrix, and when the matrix is excited with a particular light wavelength, the material will fluoresce through spontaneous emission at a longer wavelength. The corresponding florescence intensity and/or fluorescence lifetime can be utilized to measure temperature and other sensing modalities.

Despite their advantages, some optical fiber sensors have certain limitations. They have a limited temperature range, typically up to 500-600°C, and their accuracy can be affected by external factors such as strain and vibration. Other types have limited sensitivity and are susceptible to photo bleaching, which reduces their lifetime.

However, multicore fibers (MCF) sensors overcome some of these limitations and utilize a low cost interrogation method that will be discussed in more detail in the following section.

MULTICORE SENSORS

The MCF sensor offers several advantages over existing sensors, including a wider temperature range, higher sensitivity, and lower cost.

Principle of operation:

MCF sensors use closely coupled optical cores which generate supermode interference, which characteristically has a stable, high contrast, tunable interference pattern sensitive to changes in fiber temperature. The physics driving this temperature sensitivity, the thermo-optic effect, operates based on the refractive index of the MCF sensing element changing with temperature, which is an order of magnitude larger than the photo-elastic effects discussed previously. The change in refractive index causes a repeatable shift in the interference pattern between two or more supermodes in the fiber. The corresponding wavelength shift in the interference pattern can be tracked in the wavelength domain with an OSA using a broadband light source, similar to existing FBGs. However, this interference pattern can also be digitized by a low-cost photo detector using a narrow line-width light source in the power domain to generate an electrical signal proportional to temperature. The ability to interrogate the MCF sensors in the power domain significantly reduces integration costs traditionally associated with fiber optic sensors by greatly simplifying the interrogation requirements.

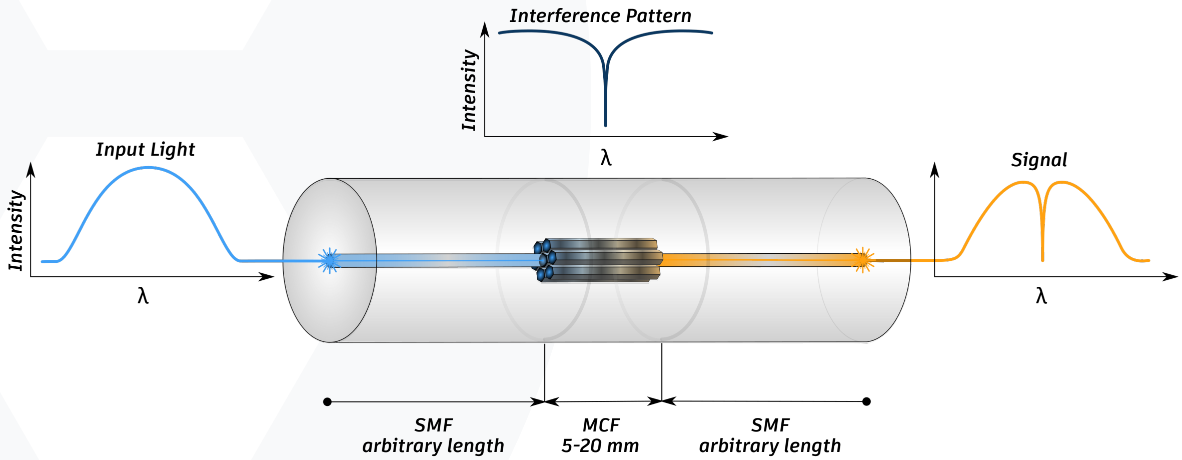

Figure 2: Operational schematic for MCF supermode interference sensing.

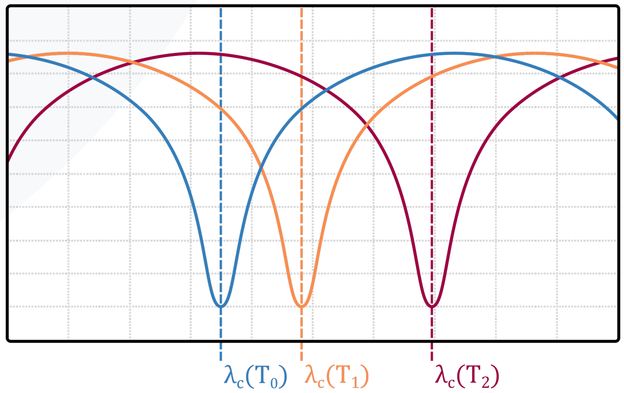

Figure 3: Example Multicore interference spectra experiencing a "Red Shift" as the fiber temperature is increased ($T_0 < T_1 < T_2$), this shift is repeatable and reversible.

PERFORMANCE COMPARISON

MCF sensors offer several advantages over other types of optical-based temperature sensors such as FBGs, FPIs, and Fluorescence-based sensors. In this section, we will compare the performance of multicore fiber sensors to these existing sensors.

Sensitivity:

MCF sensors have a high sensitivity to changes in temperature, this is primarily caused by the difference between the thermo-optic effect (the driving physics of MCF) and the photo-elastic effect (the driving physics for FBG and FPI sensors). The sensitivity of the interference pattern shifts in the wavelength domain have been documented to be 3x more sensitive (25-60 pm/°C compared to 8 pm/°C) to temperature than FBG sensors. This makes them suitable for applications where high accuracy is required, such as temperature sensing in industrial processes and power generation plants. FPIs also have high sensitivity and can exceed that of MCF sensors (100+ pm/°C), but this is for limited ranges and low temperature applications. Both FBGs and FPIs can have their accuracy affected by external factors such as strain and vibration, and designing to compensate for these factors can increase complexity. Fluorescence-based sensors have limited sensitivity compared to other optical sensors and experience significant degradation of signal quality over time, which can cause calibration errors.

Sensor Type	*Sensitivity (pm / °C)*	*Spectral Width (nm)*	*Dynamic Range (dB)*
FBG	8-20	0.1-10	20-30
FPI	5-100+	0.01-1	30-40
MCF	25-60	5-10	50-60

Table 1: Comparison of temperature sensitivity for optical sensors compared to MCF-based temperature sensors

Robustness:

MCF sensors can be less sensitive to external factors such as strain and vibration, which can affect the accuracy of other optical sensors. This makes them suitable for use in harsh environments such as oil and gas wells and aerospace applications. FBGs and FPIs can also be affected by external factors, while Fluorescence-based sensors are generally less robust than other optical sensors.

Spatial Resolution:

MCF sensors can be used for point sensing and distributed temperature sensing, where temperature is measured along the length of a fiber. However, the multiplexing capability of the MCF sensors is limited to approximately 7 channels inside the C-band, which could be a limitation when compared to FBGs. MCF temperature sensors have a low volume form factor and can provide high spatial resolution temperature measurements at a localized scale. FBGs most adopted use is for distributed sensing, where hundreds of sensors can be multiplexed on a single fiber to measure temperature along the fiber, but require more complex interrogation techniques which are very expensive. FPI and Fluorescence-based sensors generally have limited spatial resolution compared to other optical sensors and are limited to point measurements.

Range:

FBGs and FPIs have a limited temperature range of up to 500-600°C. In contrast, MCF sensors can measure temperature up to the glass transition temperature of fused silica (1000+ °C), making them suitable for high-temperature applications, such as furnace monitoring and aerospace applications. Fluorescence-based sensors have a lower effective temperature range to FBGs and FPIs and are generally not suitable for high-temperature applications as the florescent materials used in these applications degrade quickly in elevated temperature environments.

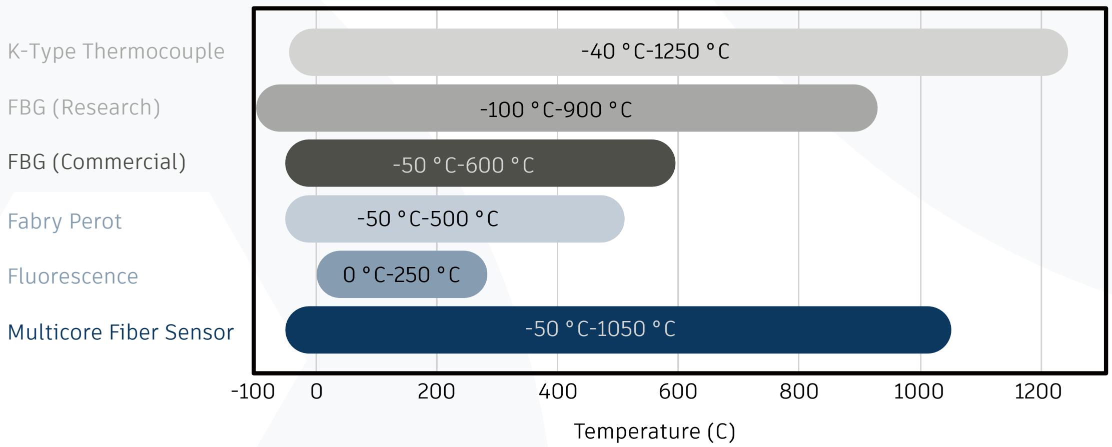

Figure 5: Comparison of operational range for optical sensors compared to Multicore fiber-based temperature sensors

Overall, MCF sensors offer several advantages over existing optical-based temperature sensors, including a wider temperature range, higher sensitivity, lower cost, and robustness. These advantages make multicore fiber sensors suitable for a wide range of applications, from industrial process monitoring to aerospace and defense applications.

COST COMPARISON

Multicore fiber has low production costs and can be made using standard fiber drawing techniques. This low-cost fiber is then assembled into temperature sensing elements using standard optical fiber splicing tools. This makes them much cheaper than other types of optical sensors such as Fluorescence, FBGs and FPIs which require more complex fabrication techniques.

Sensor Type	Materials	Manufacturing Equipment	Fabrication Complexity	Interrogation	Integration
FBG	$$	$$-$$$$	$-$$	$$$	$$
FPI	$	$$$	$$$	$$-$$$	$$
Fluorescence	$-$$	$$$	$$	$-$$	$
MCF	$	$$	$$	$	$

Table 2: Comparison of relative cost for optical sensors compared to Multicore fiber-based temperature sensors for various categories

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The total cost associated with an optical sensor system can be broken down into several key categories like raw materials, equipment, complexity, interrogation, and integration. Critical examination in each of these key areas allows for users to make informed decisions when selecting the most suitable temperature sensing approach for their specific application requirements.

Materials:

The fiber temperature sensors mentioned utilize similar doped silica glass which at manufacturing scales have a relatively low cost. The FBG and Fluorescence-based sensors have slightly higher raw material cost since the fiber has slightly different dopants to enable laser grating writing for FBG and the fluorescing dopants that are essential for Fluorescence-based sensors. MCF sensing properties are established during the draw process and are consistent for the entire drawn fiber which greatly reduces the raw material cost associated with the sensing technology.

Manufacturing Equipment:

One disadvantage most fiber sensors have in comparison to electrical sensors is that the equipment required to manufacture sensors has significantly higher cost. The most cost efficient way to manufacture FBG sensors is to write the gratings with a femtosecond laser during the drawing of the fiber which is extremely expensive. FPI and Fluorescence-based sensors both require precision alignment, cleaving and splicing capabilities to manufacture sensors which can limit scalability or dramatically increase cost at scale. MCF sensors can be constructed using standard telecom-type cleaving and fusion splicing equipment which reduces overall sensor cost and enables scale manufacturing.

Fabrication Complexity:

All sensors have an inherent complexity that can limit sensor yield and contributes to overall sensor cost due to manufacturing errors. FPI sensors require precise cavity lengths to ensure accuracy and repeatability during sensor manufacturing, mitigating these issues either increases equipment costs or decreases yield due to errors. FBG and Fluorescence-based sensors have similar complexities at manufacturing scales where loss can be mitigated with thoughtful design and large capital expenditures on equipment. MCF based sensors have low manufacturing complexity by utilizing low-cost starting materials, standard fusion splices and cleaves making the costs associated with manufacturing errors very low.

Interrogation:

Optical sensors use wavelength (FBG, FPI, MCF), intensity (FPI, Fluorescence, MCF) or phase (FBG, FPI) demodulation techniques to calculate temperature changes based on the optical signal. Wavelength and phase demodulation techniques can yield very high sensor accuracy, but this is not without a significant associated cost. To date intensity demodulation techniques have been used to provide lower interrogation cost for FPI and Fluorescence-based sensors but this cost reduction introduces a loss of sensor accuracy and range. MCF sensors are uniquely positioned to leverage either wavelength or intensity demodulation techniques without loss of function or accuracy. This cost reduction can be realized by system integrators for new systems through low-cost intensity-based interrogators or by utilizing existing wavelength-based interrogators in sensor retrofit applications.

Integration:

Traditionally, integration costs for optical based sensors have been very high and required third-party integrators to successfully deploy optical sensor systems. Typically, FBG interrogators are limited in the number of sensor input channels available and require precision switching and splitting to implement sensor chains effectively. These systems require complex software packages that can spatially realize the FBG measurement values and track temperature changes. Similarly, FPI and Fluorescence-based sensor systems can require complex splitting and switching hardware for large scale integration projects. MCF sensors represent a sensing modality that is easily scalable in the interrogator for intensity based measurements, capable of cost-effective single channel or limited multi-channel sensor integration for modular systems and integration ease similar to existing electrical based temperature sensors.

The cost associated with fiber sensing solutions has been a significant hindrance to widespread adoption of these technologies in the past. MCF based sensors are the first optical sensing technology that can be cost competitive to legacy electrical sensors in most applications when analyzing the full cost associated with system level integration of a sensor solution. The choice of sensor depends on the specific application requirements, but now with MCF sensors, users can realize the performance benefits that optical sensors provide with a cost competitive solution.

APPLICATIONS

MCF sensors have several advantages over current optical and electrical based sensors for temperature measurement.

Industrial temperature monitoring:

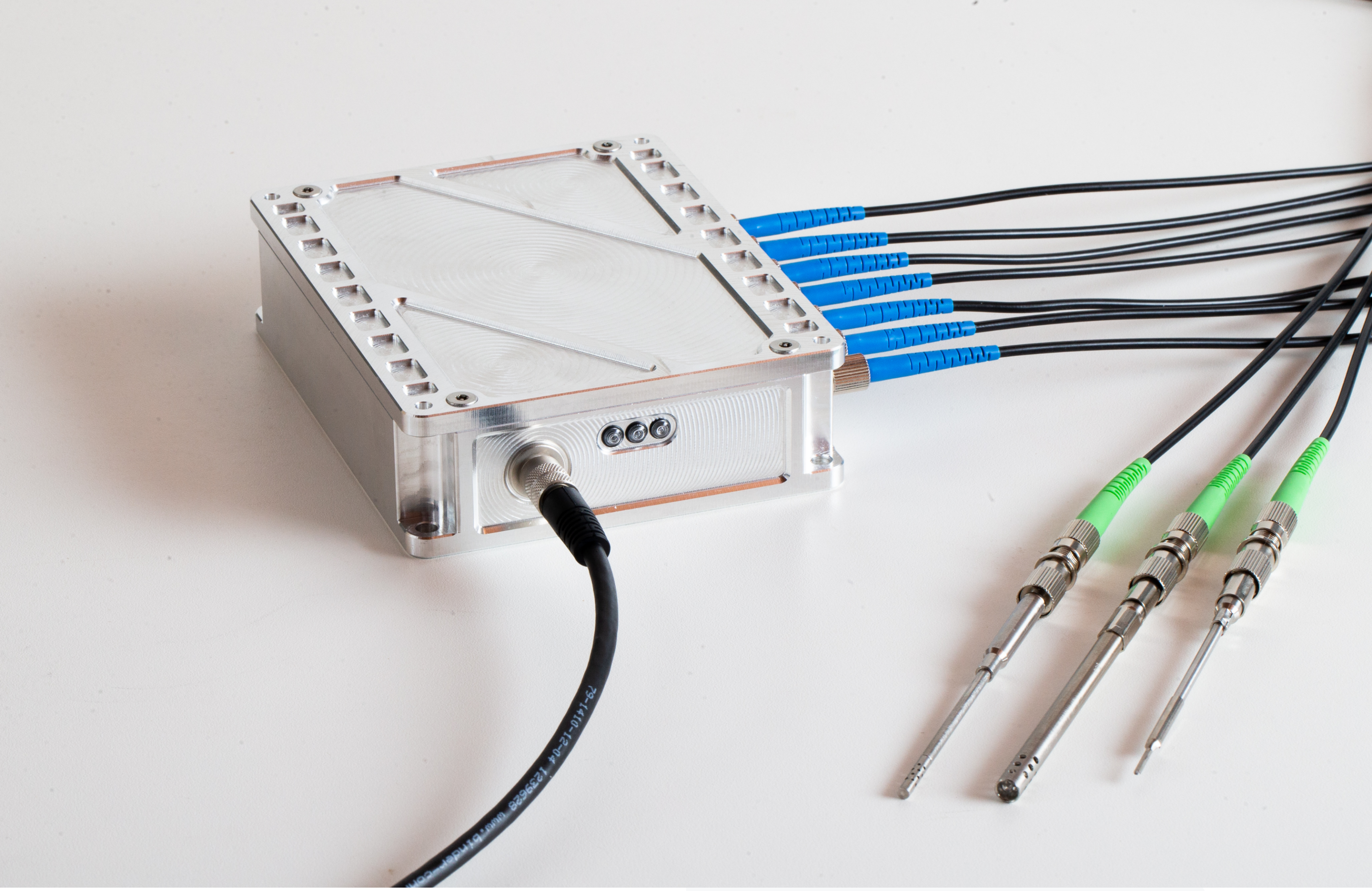
In industrial settings such as manufacturing, process control, structural health and power generation, temperature monitoring is critical to ensure efficiency, safety, and product performance. MCF temperature sensors can provide accurate and reliable temperature measurements in harsh environments, where electrical sensors may be affected by electromagnetic interference or high temperatures. For example, MCF temperature sensors can be used for temperature monitoring in gas turbines, chemical reactors, high voltage electronics (transformers, generators, etc.) and boilers, in which high temperatures, corrosive gases, and high pressures are common.

Aerospace and Defense:

In aerospace and defense applications, temperature monitoring is crucial to ensure the performance, reliability and safety of aircraft, spacecraft, missiles, and other systems. MCF temperature sensors can provide high accuracy, stability, and durability in extreme environments, including high altitude and low pressure. For example, MCF temperature sensors can be used for temperature monitoring in aircraft engines, space vehicles, and missile launchers, where high precision and reliability are essential.

Biomedical and Life Sciences:

In biomedical and life sciences applications, temperature monitoring is important for various research and clinical applications, thermal therapy, cryopreservation, and tissue engineering. MCF temperature sensors can provide high spatial resolution and sensitivity, as well as minimal invasiveness, compared to electrical sensors. For example, MCF temperature sensors could be used for temperature monitoring in tissues, cells, and microfluidic devices, where high accuracy and non-invasiveness are required.



Harsh Environment Sensing:

MCF temperature sensors excel in harsh environment sensing due to their robustness and resistance to electromagnetic interference. They are ideal for extreme conditions with high temperatures, pressures, noise, and corrosion. Industries like oil & gas exploration and automotive can benefit from these sensors to monitor equipment performance, ensure safety, and measure temperature in critical components. MCF temperature sensors provide accurate and reliable measurements in demanding industrial and engineering applications.

In summary, MCF temperature sensors offer a low cost solution with several advantages over existing optical and electrical sensors for temperature measurement in various applications, including industrial temperature monitoring, aerospace, biomedical and life sciences. MCF sensors offer high accuracy, stability, and durability in harsh environments, as well as high spatial resolution and sensitivity in non-invasive measurements.

RECOMMENDATIONS

We believe that our MCF optic temperature sensors offer a simple and cost-effective solution for high-performance temperature sensing applications in a variety of industries. If you have any further questions or are interested in exploring the potential benefits of using MCF temperature sensors in your application, we encourage you to ***contact*** our team of experts at Multicore Technologies. We have extensive experience in developing and deploying optical sensing solutions, and we would be happy to discuss your specific requirements and provide tailored recommendations. At Multicore Technologies, we are committed to making optical sensing simple for our customers