Fluorescence-Based Sensors for High-Temperature Monitoring

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Fiber-optic high-temperature sensors are gradually replacing traditional electronic sensors due to their small size, resistance to electromagnetic interference, remote detection, multiplexing, and distributed measurement advantages.

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1. Introduction

The reliable measurement of high temperatures plays a significant role in the aerospace field, metallurgical industry, and nuclear energy production [1][2][3][4][5]. For example, the application of long-range distributed high-temperature sensors guarantees the long-term safe operation of deep underground wells [6][7]. In the metallurgical industry, real-time measurement of the internal temperature of high-temperature boilers is key to monitoring combustion efficiency and safety prevention [1][8][9]. Temperature monitoring inside the combustion chambers and turbines of an aircraft or aero-engine can help extend its service life [2][10][11][12]. Extremely harsh environments with high temperatures, high pressures, and strong electromagnetic radiation present a challenge to traditional temperature sensors.

According to the installation and detection methods, high-temperature measurement technology can be mainly divided into contact measurement and non-contact measurement [3][13]. Thermocouple sensors made of precious metals are commonly used for contact temperature measurements thanks to their mature preparation process, ease of operation, wide temperature measurement range, and the capability for absolute measurements [14][15][16]. However, the thermocouple sensors have disadvantages of poor corrosion resistance, short service life, low measurement accuracy, and susceptibility to electromagnetic interference. Precious metal materials or alloys used to form thermocouple sensors are easily damaged at high temperatures, strong oxidation, or strong corrosion environments, affecting the service life and temperature measurement accuracy of thermocouples [17][18]. Infrared thermography (IRT) is representative of non-contact temperature measurement technology, which can avoid direct contact between temperature measurement equipment and high-temperature areas to achieve non-destructive testing [19][20][21]. Unfortunately, radiation temperature measurement technology is only suitable for surface measurements, such as explosion flame, and cannot detect the temperature of the internal structure of the closure device. Moreover, complex background noise is also a limiting factor in accurate temperature measurement [22].

Compared to traditional electronic sensors [2], fiber-optic sensors have attracted intensive attention during the past decades due to their inherent advantages such as compact size, flexible structure, high sensitivity, high resolution, ability to multiplex, and immunity to electromagnetic interference [23][24][25][26]. In fiber-optic high-temperature sensing systems, various optical fibers are used as the sensor transducer, as the medium for data transmission, or both [27][28]. According to the temperature measurement principle, fiber-optic sensors can be divided into blackbody radiation sensors, fluorescence-based sensors, interferometric sensors, fiber Bragg grating (FBG) sensors, and distributed temperature sensors (DTS). The commonly employed high-temperature sensing fibers mainly include silica fibers and crystal fibers. Theoretically, the maximum temperature that a temperature sensor can withstand depends primarily on the fiber material rather than the sensing mechanism. Generally, silica-fiber-based temperature sensors are limited to operating within 1000 °C due to the diffusion of germanium dopant. In addition, temperature sensors based on pure silicon fibers (e.g., photonic crystal fibers, hollow-core fibers, suspended-core fibers) can operate at 1300 °C (near the melting point of silicon), and temperature sensors based on single-crystal fibers can operate stably below 1900 °C. **Figure 1** shows the temperature sensor classification, fiber type, and sensor mechanism from the inside to the outside.

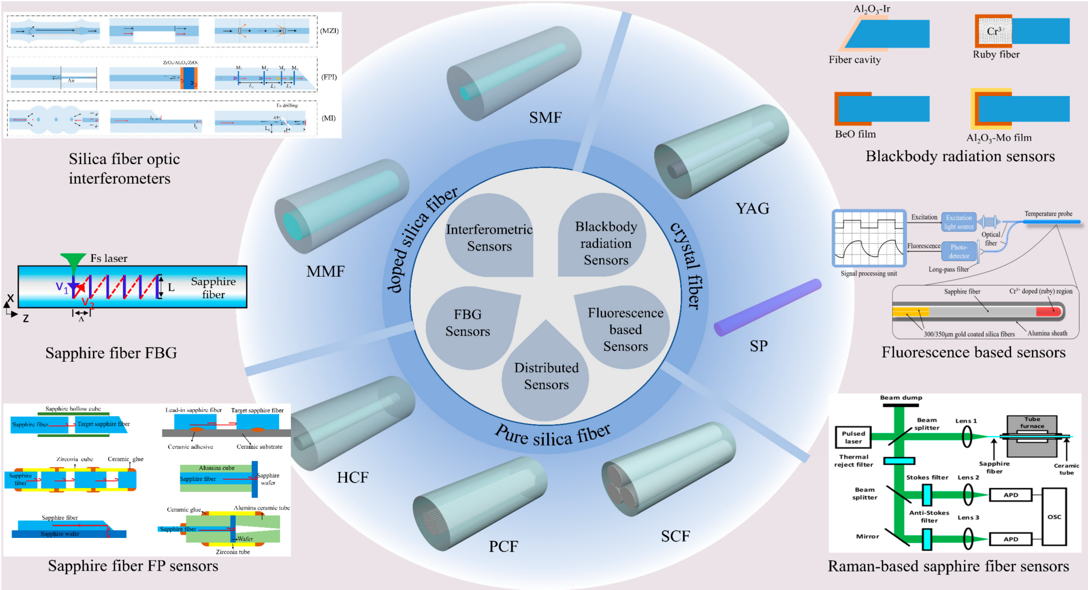

Figure 1. The temperature sensor classification, fiber type, and sensor mechanism from the inside to the outside. SP: sapphire, YAG: Yttrium aluminum garnet, SMF: single-mode fiber, MMF: multi-mode fiber, HCF: hollow-core fiber, PCF: photonic crystal fiber, SSCF: suspended-core fiber.

2. Fluorescence-Based Sensors

Fluorescence-based high-temperature sensors are generally realized by attaching various photoluminescent materials to a silica fiber or a single-crystal fiber tip such as yttrium aluminum garnet (YAG), sapphire, and $MgAl_2O_4$ by the LHPG method or co-precipitation method. When a strong laser pulse hits the fluorescent material at the probe, it generates fluorescence, which gradually decays over time (also named fluorescence lifetime). The fluorescence lifetime and fluorescence intensity of the material depends on the external temperature and generally have a linear relationship [29]. At present, two commonly used fluorescence high-temperature sensing schemes are available: one is the fluorescence lifetime (FL) method [29][30][31][32][33][34][35][36][37] and the other is the fluorescence intensity ratio (FIR) method [38][39][40][41].

The FIR method achieves temperature testing by detecting the fluorescence intensity ratio of two wavelengths at different excited states. Compared to single wavelength fluorescence intensity testing, the FIR method avoids the effects of light source intensity fluctuations. However, it suffers from some limitations in terms of performance, such as poor linearity between temperature and intensity [32]. On the other hand, the FL method does not require precise measurement of output light intensity and is not affected by fluctuations in light source intensity or external background noise, so it is widely used in commercial sensors.

Fluorescence lifetime methods have been used for sensing measurements since the 1980s, but not in fiber form [42]. With the development of optical fiber technology, optical-fiber-based fluorescent temperature sensors have been widely studied. When silicon is used as the sensor waveguide, the sensor usually operates below 400 °C. The sensor can reach a measurement value of approximately 600 °C by using a metal-coated optical fiber [43]. Later, single-crystal optical fibers were widely used in fluorescent sensors due to their higher melting point (>2000 °C), excellent mechanical properties, and extreme resistance to oxidation. In addition to the waveguide, the temperature measurement range of the sensor is also affected by the fluorescent material. **Table 1** summarizes the temperature sensing performance of fluorescence-based sensors with different doping materials in recent years. It can be found that the fluorescent material not only determines the upper limit of the measurable temperature of the sensor but also determines the sensitivity, stability, and strength of the signal under detection. For example, the burst effect of Er^{3+}-doped YAG above 600 °C causes rapid decay of fluorescence intensity and fluorescence lifetime, resulting in different sensitivity of the sensor in different temperature intervals [44]. Tm-doped Y_2O_3 has a weak fluorescence intensity, so the signal-to-noise ratio of the detected signal is poor and not suitable for high-precision measurements [45]. Therefore, the development of fluorescent sensors with high luminescence intensity and good linearity is a challenge to be faced in the future.

Table 1. Performances comparison of fluorescence-based sensors.

Test Method	Sensing Materials Doped with Rare Earths	Temperature Range	Sensing Performance	Ref.
FL	YAG: Tm^{3+}	0–1400 °C	±5 °C	2003 [29]
	YAG: Cr^{3+}	−20–500 °C	1 μs/°C @500 °C	2006 [32]
	YAG: Cr^{3+}	−25–50 °C	0.1 °C	1995 [33]
	YAG/KGW/YVO_4: Nd^{3+}	0–1000 °C	±2 °C	1997 [34]
	YAG: Yb^{3+}	1600 °C	3 °C	2002 [35]
	YSZ/YAG: Dy^{3+}	0–1200 °C	-	2009 [36]

Test Method	Sensing Materials Doped with Rare Earths	Temperature Range	Sensing Performance	Ref.
	YAG: Dy^{3+}, Er^{3+}	24–1700 °C	10 °C	2020 [37]
FIR	SiO_2/YAG: Tb^{3+}	300–1200 K	-	2006 [38]
	YAG: Pr^{3+}	293–573 K	$0.0025\ K^{-1}$	2016 [39]
	YAG: Yb^{3+}	500–1000 K	$0.3\%\ K^{-1}$	2018 [40]
	YAG: Sm^{3+}	303–1028 K	$3.046 \times 10^{-4}\ K^{-1}$	2022 [41]

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