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Feng, Yue, Wu, Haodong, Xie, Tongtong, Liu, Shouju, Luan, Tianxiang and Wang, Chao (2026) *Fully distributed in situ thermal characterization of PEM fuel cells using chirped fiber Bragg gratings*. In: *Optical Sensing and Detection IX. Proceedings of SPIE*, 14086. 140860L. SPIE

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Fully Distributed In-Situ Thermal Characterization of PEM Fuel Cells Using Chirped Fiber Bragg Gratings

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ABSTRACT

Accurate in-situ characterization of temperature gradients within the membrane electrode assembly (MEA) of proton exchange membrane fuel cells (PEMFCs) remains a significant challenge. In this work, we present a fully distributed, direct in-situ temperature sensing approach based on chirped fiber Bragg gratings (CFBGs). Exploiting the intrinsic wavelength-to-position mapping of CFBGs, 3 cm-long gratings are embedded within key MEA layers to enable spatially resolved thermal measurements. Short-time Fourier transform (STFT)-based spectroscopic demodulation is employed to reconstruct transient heat transfer and local temperature distributions with sub-millimeter spatial resolution. The proposed method exhibits a linear response over a temperature range of 30°C to 200°C, enabling continuous, high-resolution monitoring of MEA thermal gradients. This approach provides a powerful tool for real-time thermal diagnostics and performance optimization of PEMFC systems.

Keywords: Proton exchange membrane fuel cell; membrane electrode assembly; chirped fiber Bragg grating; distributed sensing; in-situ measurement; temperature gradient; optical fiber sensing

1. INTRODUCTION

Accurate thermal characterization of MEAs is crucial for optimizing PEMFC performance and service life ^[1]. The strong coupling effects in MEA lead to non-uniform and transient temperature field distributions that determine battery efficiency, material degradation, and moisture management ^[2]. Fiber Bragg gratings (FBGs) are widely used in optical fiber sensing for detecting temperature distributions. Multi-channel FBG arrays on a single fiber can achieve distributed sensing by determining temperature from shifts in Bragg wavelength^[3]. However, thermal optical effects due to temperature gradients cause a non-uniform effective refractive index distribution along the grating axis, resulting in spectral shifts and distortions^[4]. This limitation hinders applications needing millimeter-level positional resolution to accurately capture the continuous spatial distribution of measured parameters along the grating length.

In this study, a Mach-Zehnder interferometer (MZI) was constructed using two CFBGs to introduce comb-like interferometric spectra^[5]. The interferometric frequency $f(\lambda, T)$ was extracted after STFT processing. Leveraging the wavelength-position mapping characteristics of CFBGs, a distributed in-situ detection system was developed to reconstruct the transient temperature field in the grating region based on characteristic frequency wavelengths^[6].

2. PRINCIPLE ANALYSIS

The mapping relationship of CFBG from wavelength to position along the z-axis direction is^[7]:

$$z(\lambda) = \frac{\lambda/(2n_{eff}) - A_0}{C} \quad (1)$$

where A_0 is the initial period of the CFBG, C is the chirp rate, and n_{eff} is the effective refractive index. When temperature variation ΔT occurs, the phase difference changes due to thermo-optical effects and thermal expansion effects^[8], with its rate of change expressed as:

$$f(\lambda, T) = \frac{n_{eff}(T)}{\lambda} \cdot \frac{d(\Delta L)}{d\lambda} + \frac{\Delta L}{2\lambda^2} n_{eff}(T) \quad (2)$$

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where ΔL represents the equivalent length of the optical path of the reflected light at position z . Under the approximation of equal arm lengths of the MZI, the dominant term of the frequency is:

$$f(\lambda, T) \propto \frac{n_{\text{eff}}(T) \cdot C}{\lambda} = \frac{\Delta T(z(\lambda)) \cdot C}{\lambda} \cdot \frac{1}{A_0 + Cz(\lambda)} \quad (3)$$

The above equation reveals that the local temperature $\Delta T(z)$ is encoded into the interference frequency.

3. EXPERIMENTAL RESULT

The optical setup for the MZI sensing with dual CFBGs is illustrated in Figure 1(a). The sensing CFBG gate region traverses the bipolar plate channels, with temperature gradients (30–200°C) controlled by heating rods. FFT analysis of the interferometric spectrum (Figure 1(b)) identifies the dominant peak frequency range that characterizes the MZI's fundamental frequency. This peak encodes temperature-induced phase difference variations while excluding higher-order harmonics and noise components. As shown in Figure 1(c), the interferometric spectrum is normalized within 1542–1558 nm and subjected to STFT processing (1000 Hamming windows, 2^{16} FFT points) within the fundamental frequency range. The fundamental frequency extremum lines are extracted for subsequent analysis.

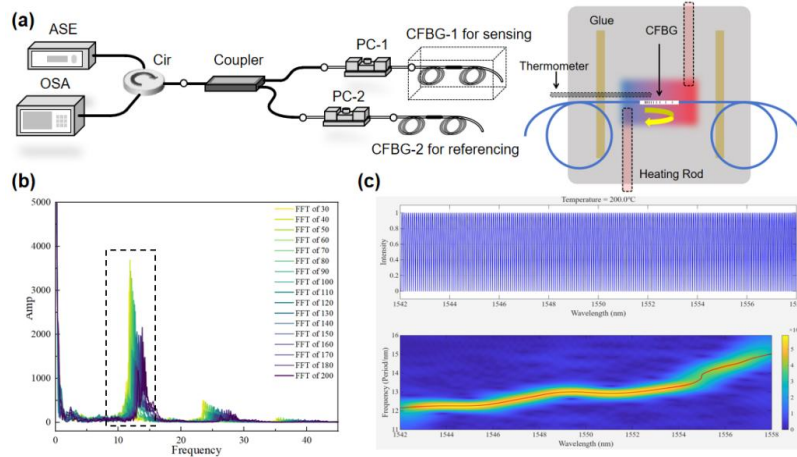


Figure 1. (a) MZI sensing optical path based on dual CFBGs, with the sensing CFBG positioned at the center of the bipolar plates. (b) Spectral FFT determines the fundamental frequency range. (c) STFT frequency extraction (200°C).

Figure 2(a) shows an overall increase in frequency with rising temperature, accompanied by a more pronounced long-waveband response. The temperature sensitivity relationship can be derived by taking the partial derivative of T with respect to Equation (3). Figure 2(b) and (c) show that bipolar plates have distinct frequency anomalies when the front or rear half of the gate region is heated. Heating the front gate region keeps the response at 1552 nm and introduces a frequency gap in subsequent wavelengths, whereas heating the rear region maintains the response at 1550 nm but introduces a frequency gap in preceding wavelengths. These observations confirm the wavelength-position mapping relationship in Equation (1).

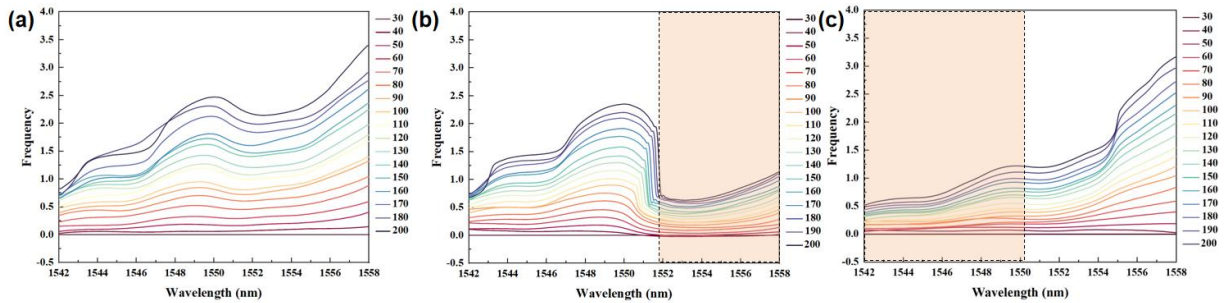


Figure 2. (a) Temperature response of homogeneous temperature field, (b) Temperature response enhanced by gradient field, (c) Temperature response attenuated by gradient field (direction from short-period to long-period in the gate region)

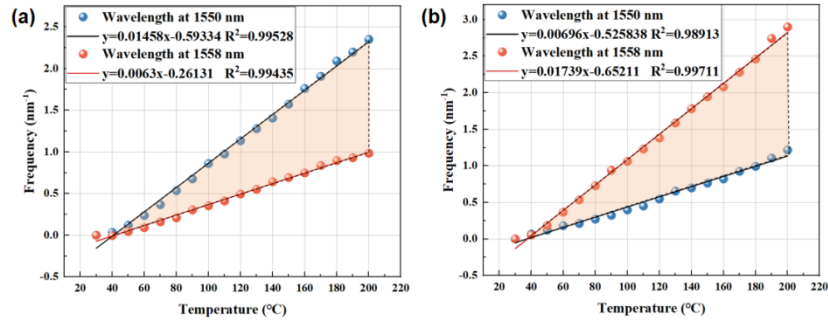


Figure 3. Sensitivity fitting of characteristic wavelength (a). Gradient field enhancement (b). Gradient field attenuation

For the frequency response shown in Figure 2(b), (c), frequency value sensitivity fitting was performed at characteristic wavelengths λ_n (1550 and 1558 nm) adjacent to the central wavelength. The results are illustrated in Figure 3(a) and (b), demonstrating that $d f(\lambda_n, T)/dT$ maintains linearity under temperature gradient field effects. The angular difference between the fitting curves for λ_{1550} and λ_{1558} can be used to characterize temperature-gradient gaps. Based on physical sensor analysis, where the characteristic wavelength difference is denoted as $\Delta\lambda$, the theoretical spatial resolution for temperature detection in this approach is given by $\Delta z = \Delta\lambda/(2n_{eff} C)$, achieving sub-millimeter-level temperature-gradient detection accuracy.

In conclusion, this study validates encoding local temperature into interferometric frequencies, enabling the inversion of temperature gradients to physical locations via wavelength-position anomalies in the frequency amplitude. This technology offers a powerful diagnostic tool for understanding internal thermal behavior and supports real-time feedback control in advanced PEMFC systems.

ACKNOWLEDGEMENTS

This work was supported in part by the Program for Young Talents of Basic Research in Universities of Heilongjiang Province under Grant YQJH2025065, and in part by UKRI/InnovateUK under Project Reference 10097017.

REFERENCES

- [1] Su, H., Xu, H., Wang, L., et al. "A review on thermal management strategy for liquid-cooling proton exchange membrane fuel cells: Temperature regulation and cold start," *Applied Energy*, 2025, 393: 126142.
- [2] Veza, I., "Fuel-cell thermal management strategies for enhanced performance: review of fuel-cell thermal Management in Proton-Exchange Membrane Fuel Cells (PEMFCs) and solid-oxide fuel cells (SOFCs)," *Hydrogen*, 2025, 6(3): 65.
- [3] Wang, J., Li, Z., Fu, X., et al. "Distributed temperature sensing system based on a densely spaced FBG array for small fire recognition," *Measurement*, 2021, 179: 109406.
- [4] Li, X., Chong, Y., Wang, J., et al. "A linear chirp fiber Bragg grating with tunable bandwidth enabled by MXene's photothermal effect," *Applied Physics Letters*, 2023, 123(16).
- [5] Ahmad, E. J., Wang, C., Feng, D., Yan, Z., and Zhang, L., "High temporal and spatial resolution distributed fiber Bragg grating sensors using time-stretch frequency-domain reflectometry," *Journal of Lightwave Technology*, 35, 3289-3295 (2017).
- [6] Nand, A., Kitcher, D. J., Wade, S. A., et al. "Determination of the position of a localized heat source within a chirped fibre Bragg grating using a Fourier transform technique," *Measurement Science and Technology*, 2006, 17(6): 1436-1445.
- [7] Poozesh, R., Madanipour, K., Vatani, V., "Spectral interference fringes in chirped large-mode-area fiber Bragg gratings," *Optical Fiber Technology*, 2016, 31: 134-137.
- [8] Xie, Z., Li, P., Guo, D., et al. "Refined spectral regulation of chirped fiber Bragg gratings," *IEEE Photonics Technology Letters*, 2024, 36(7): 520-523.