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Miniature optical fiber Fabry-Perot sensor based on PDMS end-cap structure

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Abstract: This paper presents a method for fabricating a low-cost, highly reproducible miniature optical fiber Fabry-Perot (FP) sensor based on a polydimethylsiloxane (PDMS) end-cap structure. The FP cavity end-cap is formed by the optical fiber end-face and a PDMS droplet deposited onto it. The PDMS deposition is achieved by immersing the fiber end into pre-cured PDMS at a fixed speed, a process requiring careful control of PDMS viscosity and surface tension. By leveraging PDMS's excellent thermal expansion coefficient, Poisson's ratio, and other parameters, this method achieves high reproducibility via viscosity-optimized pre-curing, enhanced sensitivity for temperature measurements, and significant cost reduction versus commercial counterparts. Fiber FP sensors are increasingly widely used in biomedical and precision detection fields owing to their significant advantages, including small size, light weight, high sensitivity, and immunity to electromagnetic interference. In the fabrication of fiber FP sensors, using polymer materials is an effective technical approach. These polymers can be applied as coatings on the optical fiber end-face or as interlayer materials embedded between fibers to form the FP cavity structure, which not only significantly improves the overall sensor performance, but also enhances its sensitivity to changes in temperature, pressure, and refractive index. In the final part of this study, we successfully validated the exceptional performance of the PDMS end-cap based fiber FP sensor in detecting different temperatures conditions. Experimental results demonstrate a temperature sensitivity of 0.752 nm/℃ for sensors with a 60-μm PDMS end-cap, further confirming the sensor's reliability and efficiency in practical applications.

Key words: fiber Fabry-Perot (FP) sensor; polydimethylsiloxane (PDMS); carbon nanopartides (CNPs)

0 Introduction

Fiber-optic sensor technology currently demonstrates excellent performance in the field of optical parameter monitoring, enabling precise measurement of key indicators such as absorbance, reflectivity, and refractive index[1-4]. These measurements are significantly influenced by physicochemical conditions within the analytical environment, including temperature, barometric pressure, and humidity levels[5,6]. With the continuous advancement of optical fiber manufacturing technology, fiber-based sensors have achieved widespread application. Among these, fiber-optic Fabry-Perot(FP) sensors hold a prominent position in the detection of physicochemical parameters[7,8]. This technology has been successfully applied to the accurate measurement of parameters including temperature, pressure, strain, and molar concentration, serving as an integral component of high-precision sensing systems.

The fabrication of fiber-optic FP sensors encompasses diverse technical approaches such as laser micromachining, fusion splicing, and chemical etching. Polymer coating techniques applied to optical fiber end-faces have garnered substantial research interest owing to the direct deposition capability of polymeric materials through dip-coating processes and their efficient curing and adhesion on fiber termini[9]. Multiple polymers have demonstrated suitability for constructing end-cap FP cavity structures, enabling high-precision monitoring of parameters including temperature, pressure, refractive index, humidity, and concentration. Among polymeric materials, polydimethylsiloxane (PDMS) exhibits distinctive advantages including superior optical properties for temperature sensing applications, exceptional electrical insulation, chemical stability, and hydrophobicity ensuring measurement stability in humid environments, and operational reliability across a broad temperature range (—50—200 ℃)[10]. These characteristics position PDMS advantageously for automotive sensing applications, facilitating real-time monitoring of critical parameters such as engine temperature, lubricant quality, and tire pressure. This capability contributes to vehicle performance optimization, enhanced driving safety, proactive fault prevention, and advancement of intelligent driving technologies[11,12]. The material's excellent biocompatibility and non-toxicity render it suitable for wearable devices. PDMS's low surface energy enables non-destructive demolding post-curing—a property that significantly advances research on PDMS-based fiber-optic FP sensors with notable theoretical and practical significance.

Significant advancements in fiber-optic FP sensor technology have emerged globally in recent years. In 2008, Tseng et al. deposited PDMS on single-mode fiber with an additional gold layer on the PDMS end-face to enhance reflectivity, achieving immunosensing for rabbit IgG antigen[13]. In 2016, Hernández-Romano et al. fabricated an intrinsic FP cavity by coating TiO_2 on one fiber end and PDMS on the opposite end, utilizing PDMS's high thermo-optic coefficient to achieve an extinction ratio sensitivity of 0.13 dB/℃ within 22—60 ℃[14]. Polymer-integrated FP sensors offer advantages including miniaturization, simplified fabrication, and substantial development potential. This research demonstrates PDMS's capability to enhance sensor performance while providing novel approaches for developing multifunctional, high-sensitivity environmental monitoring sensors, expanding precision sensing applications in environmental surveillance and biological detection[15].

Consequently, this study employs PDMS as the FP cavity medium, leveraging its pronounced thermo-sensitivity and favorable elastic modulus to enhance temperature and pressure response capabilities. To further improve sensitivity and interference contrast in PDMS-based sensors, we investigated how PDMS's thermal expansion, thermo-optic properties, and Poisson's ratio influence geometric parameters and temperature sensitivity. Results demonstrate that the proposed methodology effectively utilizes PDMS's thermal expansion coefficient and Poisson's ratio, significantly enhancing fiber-optic sensor temperature sensitivity and yielding substantial performance optimization in practical implementations.

1 Principle and preparation

1.1 Principle

The core component of a fiber-optic FP sensor is an optical cavity formed by two parallel reflective surfaces, being capable of generating exceptionally fine interference fringes with high finesse. Consequently, it finds extensive application in length measurement and spectroscopic analysis of hyperfine structures[16]. Fiber-optic FP sensors evolved from this principle, typically implementing sensing functions through cavities formed by two low-reflectivity reflective surfaces within optical fibers.

During light propagation through optical fibers, refractive index mismatches at material interfaces cause refraction and reflection. This inherent property facilitates the establishment of reflective surfaces within optical fibers, thereby forming FP interferometric cavities. Given the low reflectivity of these interfaces, their interference signals can be accurately described using multi-beam interference theory. The narrow definition of an FP cavity refers to a structure with strictly parallel reflective surfaces. However, advancements in fiber micro-machining technology and adaptation to diverse application requirements have expanded this definition. Contemporary configurations permit non-parallel reflective surfaces with curved or other geometrical profiles, establishing the concept of generalized FP cavities[17].

The complete sensor system comprises a sensing element incorporating an FP cavity and a demodulation subsystem. When subjected to external environmental variations, the PDMS end-cap undergoes deformation due to applied stimuli, consequently altering the FP cavity length. Optical signals propagate through the optical fiber to the demodulation subsystem, enabling precise determination of external parameter changes such as temperature or pressure[18]. As illustrated in Fig.4, the sensor structure consists of a PDMS end-cap integrated with a single-mode optical fiber. The fabrication process involves first polishing the optical fiber end-face to optical flatness followed by thorough cleaning. The prepared fiber end is then immersed at a controlled speed into pre-cured PDMS, resulting in a FP cavity end-cap formed by the fiber end-face and the deposited PDMS droplet adhering to it.

1.2 Preparation

The fabrication of PDMS-based fiber-optic FP sensors involves a series of precision optical fiber processing and material deposition steps. Initially, fiber end-face pretreatment employs high-precision cleaving to ensure optical flatness, followed by ultrasonic cleaning. Subsequently, PDMS solution preparation and deposition are performed by immersing the fiber end-face into a rigorously controlled PDMS prepolymer solution (with precise temperature, concentration, and solvent formulation ratios). Through capillary action and surface tension, the PDMS prepolymer aggregates on the fiber end-face to form the required FP cavity structure.

Following PDMS prepolymer deposition, localized laser heating is applied to cure the PDMS end-cap. This process requires precise control of laser power and exposure duration to prevent fiber damage or uneven PDMS layer formation. Finally, reflectance spectral characterization is conducted: The cured PDMS end-cap forms a sealed FP cavity, Throughout sensor fabrication, an micro-optical interferometer (MOI Model: TV130, Tongwei Sensing) with its dedicated software (FODS v3.2, Tongwei Sensing) enabled real-time monitoring of FP reflection signals. This step verifies cavity construction quality and evaluates optical performance. Detailed procedures and experimental results demonstrate the reproducibility and process efficiency of this fiber-optic FP sensor fabrication methodology, as illustrated in the accompanying Fig.1.

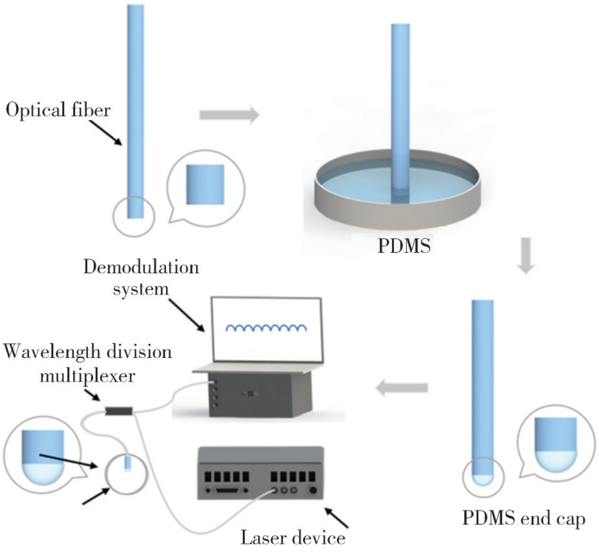


Fig. 1 Sensor fabrication process

In the fiber end-face cleaning and planarization phase, the experimental protocol employed a specialized fiber end-face polishing machine for precision grinding, followed by ultrasonic cleaning using an industrial-grade ultrasonic cleaner. Throughout this process, real-time quality verification was conducted with a fiber end-face inspection system to quantitatively evaluate surface roughness and contamination levels. This integrated approach ensured optimal end-face morphology essential for subsequent polymer deposition and optical performance.

Following the completion of the fiber end-face polishing and cleaning procedures, this study further investigated the dip-coating process for PDMS application on optical fiber end-faces. We developed an innovative yet straightforward technique for fabricating PDMS end-caps with high reproducibility. The core concept involves pre-curing PDMS under controlled temperature conditions to modify its rheological properties (specifically viscosity and surface tension), enabling precise deposition onto cleaved fiber end-faces. By meticulously matching dip-coating parameters with PDMS pre-curing conditions, we achieved batch production of dimensionally uniform PDMS end-caps exhibiting consistent spectral characteristics.

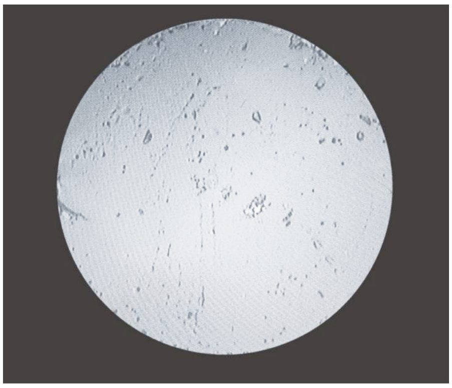


Fig. 2 Optical fiber end-face microscope after cleaning and grinding

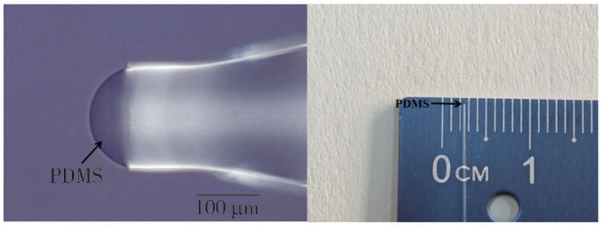
For the sensor end-cap material, we employed Sylgard 184 PDMS (Dow Corning, USA). The fabrication protocol initiates with thoroughly mixing the PDMS base and curing agent at a 10 : 1 mass ratio, followed by vigorous stirring to generate air bubbles. The homogeneous mixture is subsequently degassed until complete bubble dissipation. Approximately 2 mL of the degassed PDMS solution is then transferred to a temperature-controlled heating stage for pre-curing, maintaining constant temperature throughout the dipping process. Experimental optimization determined a 10-min pre-curing duration as optimal.

We systematically investigated the effect of pre-curing temperature on achieving target surface tension for dimensionally consistent end-caps. At a fixed 50 ℃ pre-curing temperature, insufficient polymer adhered to the fiber tip, yielding end-caps unsuitable for sensing applications. Pre-curing at 70 ℃ consistently produced adequate polymer volume for subsequent curing, achieving the desired end-cap thickness. However, elevating the temperature to 80 ℃ induced filamentation due to altered surface tension during fiber withdrawal, rendering the resulting structures unsuitable for sensor end-caps.

After establishing optimal pre-curing conditions, standard single-mode fibers (SMF-28e, Corning, USA) underwent precision cleaving and polishing. The prepared fiber end-face was vertically immersed into the pre-cured PDMS solution. Controlled withdrawal at a constant speed produced a hemispherical cap-shaped PDMS droplet on the fiber end-face.

Throughout the sensor fabrication process, a micro-optical interferometer and its proprietary software enabled real-time monitoring and adjustment of the FP sensor's reflection signals, with automated acquisition of spectral domain data. For each manufactured sensor, detailed reflection spectral characteristics and corresponding imaging data were systematically recorded for subsequent analysis.

Finally, PDMS-coated optical fiber end-face was vertically positioned and subjected to laser irradiation to ensure complete PDMS curing while monitoring real-time data. Under specified curing conditions, the PDMS end-cap-based fiber sensor fabrication process was completed within 30 min, successfully yielding operational PDMS-structured fiber-optic FP sensors. Fig. 3(a) shows the microscopic magnification of the PDMS end-cap, while Fig. 3(b) displays the physical photograph of the sensor.



(a) Microscope image (b) Physical image

Fig. 3 PDMS end-cap based fiber-optic sensor

2 Test and analysis of sensor performance

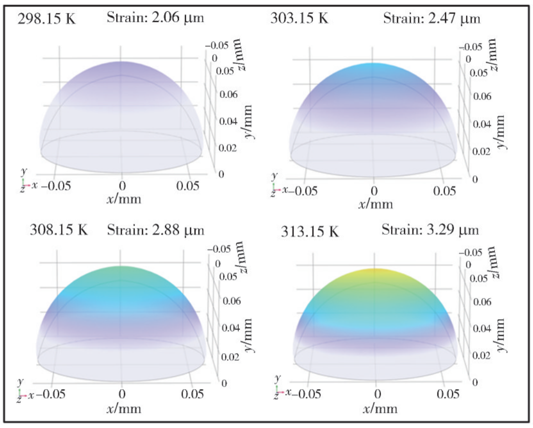
2.1 Sensor performance simulation

The operational principle of PDMS-based fiber-optic FP sensors relies on the interference effects within the FP cavity, where variations in cavity length directly influence the sensor's output signal. Consequently, investigating temperature-induced cavity length variations is crucial for comprehensively understanding the sensor's working mechanism and optimizing its design. This study aims to establish a theoretical foundation for the cavity length variation patterns in PDMS fiber-optic FP sensors under thermal fluctuations, thereby supporting performance analysis and structural optimization.

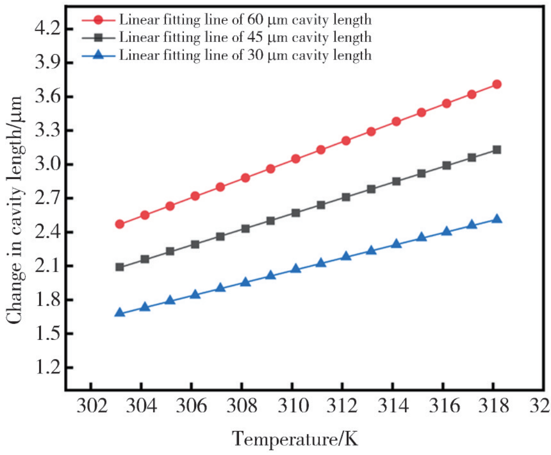
To achieve this objective, finite element simulations were conducted using COMSOL Multiphysics software. Through computational modeling, we identified and optimized key performance-influencing parameters—including FP cavity dimensions—to enhance sensor characteristics such as sensitivity and linear response characteristics. In the sensor design phase, PDMS was selected as the end-cap substrate material. A three-dimensional finite element model of the sensor end-cap was developed, incorporating PDMS's physical properties: elastic modulus, density, and Poisson's ratio. To ensure simulation accuracy, appropriate displacement constraints were applied to align with experimental conditions.

This methodology provides scientific insights into the thermal performance of PDMS fiber-optic FP sensors and guides structural refinements for achieving enhanced efficiency and heightened precision in sensing applications.

During the finite element simulation phase, we first investigated the effect of temperature variations on the FP cavity length within the fiber sensor's end-cap. The temperature range was systematically increased from 30 ℃ to 45 ℃ at equidistant increments of 1 ℃. Throughout this thermal gradient progression, strain data from the model were recorded and analyzed in detail. Simulation results presented in Fig.4(a) illustrate strain distributions for a 60-μm end-cap at different temperatures, while Fig.4(b) quantifies cavity length variations corresponding to temperature simulations for different end-cap dimensions. These cavity length changes align precisely with theoretical predictions.



(a) Strain distribution at different temperatures



(b) Change in cavity length

Fig. 4 Simulation results of 60-μm end-cap

The study conclusively demonstrates that optimal sensor performance is achieved when the FP cavity length approximates 60 μm. This finding provides critical reference data for optimizing fiber-optic sensor design, ensuring maximum sensitivity and optimal linear response in practical implementations.

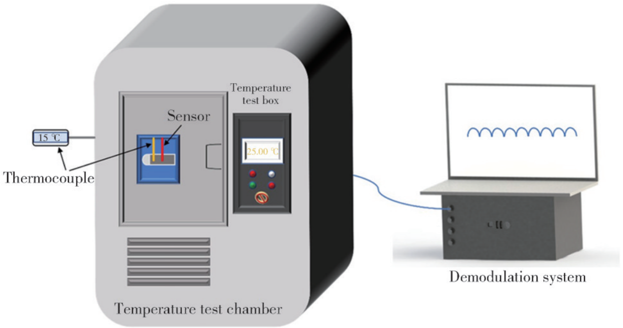
2.2 Temperature test

The modulation of spectral responses in fiber-optic FP sensors fundamentally relates to the structural characteristics of the FP cavity. These spectral features are influenced by environmental refractive index surrounding the end-cap, as well as parameters including temperature and pressure. Temperature variations induce spectral shifts through thermal expansion and thermo-optic effects, while pressure causes spectral displacements via end-cap deformation and the piezo-optic effect. Changes in ambient refractive index primarily affect the extinction ratio (or contrast) of the optical signal. This phenomenon is universally observed in fiber-optic sensors employing conventional polymeric end-caps.

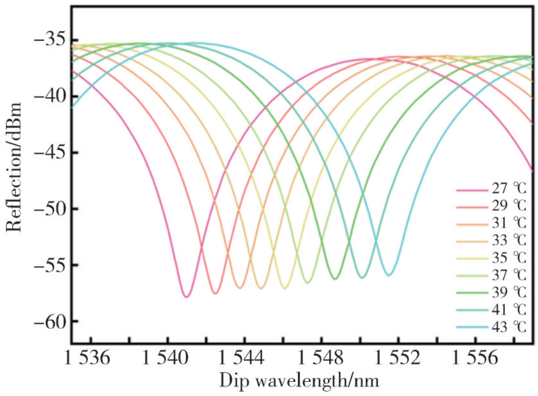
Following comprehensive evaluation of critical performance metrics—including interference spectral contrast, sensitivity, and manufacturing precision—we selected a sensor with optimized structural parameters. This sensor incorporates a PDMS end-cap approximately 60 μm in length. This section experimentally investigates the sensor's temperature-sensing performance to validate its suitability and reliability as a temperature transducer.

As illustrated in Fig. 5(a), the fabricated sensor was positioned within a precision incubator using a dedicated temperature-sensing test system. Reverse reflection signals from the sensor end-cap were continuously recorded throughout the experiment. By systematically adjusting the incubator temperature from 27 ℃ to 43 ℃ in 2 ℃ increments, we acquired interference spectra across this thermal range. To ensure measurement accuracy, spectral acquisitions commenced only after a 20-min stabilization period following each temperature adjustment. The sensor was enclosed in a chamber with a temperature-controlled stage. The thermal controller executed heating/cooling cycles between 27 ℃ and 43 ℃ (2 ℃ steps, 5-min dwell time, 1 Hz sampling rate). For calibration, thermistors and thermocouples were collocated as reference temperature sensors alongside the FP sensor.

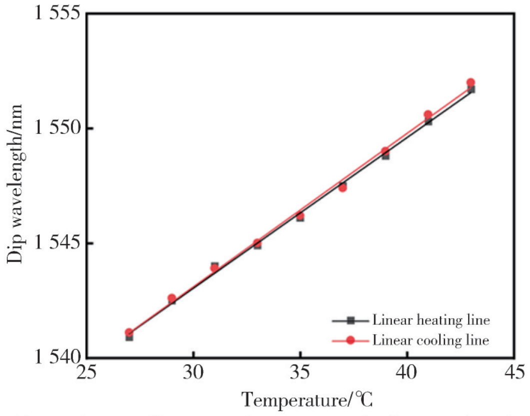
Spectral drift occurred without mode hopping during measurements. Fig. 5(b) presents the acquired interference spectra under temperature variation, while Fig. 5(c) displays the fitted relationship between valley wavelengths and temperature during heating/cooling cycles. Using peak detection algorithms to track interference valley shifts, we determined a temperature sensitivity of 0.752 nm/℃ with high linearity.



(a) Schematic diagram of temperature measurement setup



(b) Interference spectra of sensor at temperatures ranging from 27 ℃ to 43 ℃



(c) Fitted curve illustrating the variation of valley wavelengths with temperature

Fig. 5 Performance test

As shown in Table 1, we compared our sensors with some literature reports.

Table 1 Comparison with other temperature sensors

Sensor	Measuring range/℃	Sensitivity/nm	Ref.
Fiber-optic high-temperature sensor based on thin-core fiber modal interferometer	25—850	0.018 30	[19]
Double polymer-capped FPI	20—75	0.689 68	[20]
High-sensitivity SPR temperature sensor based on hollow-core fiber	35.5—70.1	1.160 00	[21]
Miniature optical fiber FP sensor based on PDMS end-cap structure	20—100	0.752 00	**Our work**

3 Conclusions

In summary, the proposed PDMS end-cap-based fiber-optic FP sensor demonstrates significant applicability for biomedical and automotive applications due to its high temperature sensitivity, compact dimensions, and simplified fabrication process. Specifically, this sensor enables precise monitoring of intravascular and visceral temperatures, providing critical data for clinical diagnostics. Within the automotive sector, it facilitates real-time measurement of engine temperature, lubricant oil condition, and tire pressure, delivering cost-effective data to enhance vehicle safety and operational reliability. This research establishes a scientific foundation and technical reference for multi-domain implementation of fiber-optic FP sensors.

The study presents an innovative sensor fabrication technique centered on direct polymer end-cap formation at the optical fiber core terminus. This approach significantly streamlines manufacturing by eliminating traditional complex optical alignment requirements. Spectral characteristics exhibit direct correlation with end-cap thickness, with all tested sensors demonstrating suitable spectral responses for sensing applications. Particularly, the sensors achieved substantially enhanced temperature sensitivity compared to conventional end-sealed devices, attributable to precise dimensional control and PDMS's optimized optical-mechanical properties. The methodology extends beyond PDMS to other materials, permitting further optimization of thermal and mechanical responses under varying operational conditions. This adaptable manufacturing process offers novel design possibilities for highly sensitive, miniaturized sensing solutions in biomedical monitoring, environmental detection, and industrial automation.

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Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

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基于PDMS端盖结构的微型光纤法珀传感器

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摘　要：本文展示了一种制造简易、成本低廉且具有高重复性的基于聚二甲基硅氧烷(Polydimethylsiloxane, PDMS)端盖结构的微型光纤法珀(Fabry-Perot, FP)传感器。法珀腔端盖由光纤端面和沉积在光纤端面的PDMS液滴组成，其中，PDMS的沉积是通过将光纤端以固定的速度浸入预固化的PDMS中来完成的，其过程要保持一定的PDMS粘度和表面张力。利用PDMS优秀的热膨胀系数、泊松系数等参数，提高了传感器在温度以及压力测量时候的灵敏度；光纤的端面包含一层碳纳米颗粒(Carbon nano particles, CNPs)，从激光器发射激光通过光纤时，利用碳纳米颗粒提升折射率、均匀尺寸等优势，加强了传感器在温度压力等方面的测量。光纤法珀传感器以其体积小、质量轻、灵敏度高以及不受电磁干扰等显著特点，在生物医疗和精密探测等多个领域逐渐获得了广泛的应用。在光纤法珀传感器的制造过程中，采用聚合物材料是一种有效的技术途径，这些聚合物可以作为涂层涂覆在光纤表面，或者作为夹层材料嵌入光纤之间，以形成法珀腔结构。这种聚合物应用不仅显著提升了传感器的整体性能，还增强了其对温度、压力和折射率变化的灵敏度。在本研究的最后部分，我们成功地验证了基于PDMS端盖结构的光纤法珀传感器在检测不同温度或不同气压条件下的优异表现，进一步证实了该传感器在实际应用中的可靠性和高效性。

关键词：光纤法泊传感器；聚二甲基硅氧烷；碳纳米颗粒

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