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# Research Status of High-Temperature Fiber-Optic Sensors Based on Fabry-Perot Interferometry

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## Abstract

**The measurement of physical parameters under high-temperature environments is widely needed in fields such as aerospace engines (e.g., ramjet engines and supersonic combustion ramjet engines), gas turbines, and hypersonic vehicles. Monitoring and evaluating combustion instability phenomena through pulsating pressure measurements is beneficial for studying the mechanisms behind combustion instability, providing a basis for physical structural improvements of combustion chambers as well as for engine design and evaluation. It also contributes to improving engine control performance and operational safety. Fiber-optic sensing technology based on Fabry-Perot (FP) interferometry has attracted significant attention due to its advantages of small size and high-temperature resistance, which enable it to measure physical parameters in harsh environments such as in aerospace engines. This paper reviews domestic and international research on fiber-optic sensors based on FP interferometry. The focus is on analyzing the advantages and disadvantages of various fabrication methods for fiber-optic sensors, with the aim of summarizing the characteristics of each technique and providing new ideas for the engineering application of high-temperature fiber-optic FP sensing technology.**

## Keywords

**Fiber-optic Fabry-Perot, high-temperature environment, sensor, research status.**

## Introduction

Fiber-optic sensors hold a very important position in the field of sensing technologies. Compared with traditional electrical sensors, fiber-optic sensors offer many outstanding advantages, such as resistance to electromagnetic interference, high resolution, high accuracy, small size, long transmission distance, and the ability to operate in harsh environments such as high temperatures and corrosive conditions. The working principle of a fiber-optic pressure sensor is that the sensing element modulates certain parameters of the optical system, such as intensity, wavelength, polarization, and phase, in response to applied pressure. These changes alter the characteristics of the optical signal received by the detector. By demodulating the changes in the optical signal, pressure measurement can be realized. According to the type of optical signal modulation, fiber-optic pressure sensors can be categorized into intensity-modulated, wavelength-modulated, polarization-modulated, and phase-modulated types.

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Among them, phase-modulated fiber-optic pressure sensors typically utilize optical interference methods to achieve phase modulation. Based on different optical interference principles, phase-modulated fiber-optic pressure sensors can be classified into Michelson interferometer type, Mach-Zehnder interferometer type, Sagnac interferometer type, and Fabry-Perot (FP) interferometer type. The fiber-optic Fabry-Perot pressure sensor is one of the most important types among them. Currently, there are many methods for fabricating fiber-optic Fabry-Perot pressure sensors, including arc discharge technology, chemical etching technology, laser processing technology, fusion splicing technology, bonding technology, 3D printing technology, LTCC (low-temperature co-fired ceramic) technology, and MEMS technology. The following sections will analyze and elaborate on the research status of fiber-optic Fabry-Perot pressure sensors at home and abroad according to different fabrication methods.

## 1. Arc Discharge Technology

Arc discharge technology mainly utilizes the arc discharge of a fiber fusion splicer to fabricate and construct the pressure-sensitive component and Fabry-Perot (FP) cavity structure of a fiber-optic Fabry-Perot pressure sensor. At present, the most commonly used method is to directly fabricate a microsphere structure on the fiber as the Fabry-Perot interferometer, or to use arc discharge on a hollow quartz tube to fabricate a microsphere structure, which is then integrated with a single-mode fiber to form a Fabry-Perot interferometer. Fiber-optic Fabry-Perot pressure sensors fabricated by this method have the advantages of small size and simple process, but are usually manufactured individually, and require precise adjustment of the fusion splicer’s discharge power and duration, making it difficult to ensure consistency among sensors.

Wang et al. from Shenzhen University fabricated a fiber-tip Fabry-Perot pressure sensor using arc discharge technology with a fiber fusion splicer. The minimum thickness of the sensor's sensitive diaphragm is approximately 320 nm. The sensitivity of this sensor is about 1036 pm/MPa, and the temperature cross-sensitivity coefficient is approximately 960 Pa/°C. The test temperature range is 20 °C–100 °C [1], as shown in Fig. 1(a). An et al. from Shenzhen University used a fiber fusion splicer and pressure-assisted arc discharge technology to fabricate a quartz hollow microbubble from an ordinary glass tube with thin-film characteristics. A single-mode fiber was then inserted into the microbubble. By measuring the interference spectrum of the Fabry-Perot interferometer formed between the fiber tip and the inner surface of the microbubble, a fiber-optic pressure sensor with high sensitivity was realized. This sensor has a pressure sensitivity of 164.56 pm/kPa, and a temperature sensitivity of 4 pm/°C within the temperature range of 40 °C–120 °C [2].

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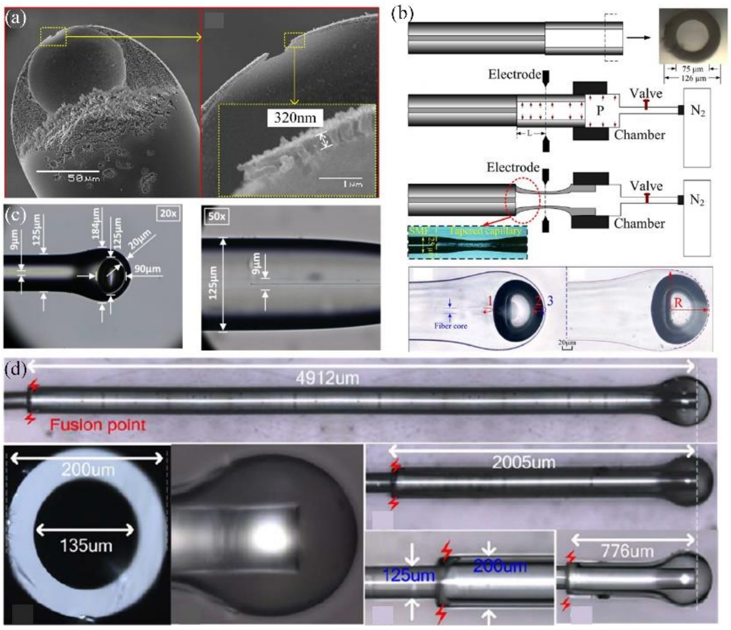


**Fig. 1** (a)–(d) Optic-fiber FP Pressure Sensor fabricated by arc discharge technology.

Zhang et al. from Beijing Information Science and Technology University fabricated a spherical Fabry-Perot interferometer using arc discharge technology with a fiber fusion splicer, and integrated it with a fiber Bragg grating to produce a fiber-optic temperature and pressure sensor capable of simultaneous measurement. The temperature test range is 40 °C–400 °C, and the pressure test range is 0 MPa–2 MPa [3], as shown in Fig. 1(c). Jin et al. from The Hong Kong Polytechnic University developed a fiber-tip microcavity pressure sensor using a fusion splicer and a pressurized gas chamber. A section of hollow quartz capillary tube was fused to the single-mode fiber. Under pressure and arc discharge from the splicer, the quartz capillary was tapered and fractured, with part of it remaining attached to the fiber end face, forming a spherical structure internally. The inner surface of the microsphere and the fiber end face act as the two reflective surfaces of the Fabry-Perot cavity. Pressure changes cause deformation of the microsphere shape, thereby changing the cavity length. This sensor achieved high-temperature pressure measurements at 600 °C, with a pressure sensitivity of approximately 315 pm/MPa [4], as shown in Fig. 1(b). Jia et al. from North University of China fabricated a high-temperature fiber-optic Fabry-Perot pressure sensor with a microbubble structure and low temperature coefficient using arc discharge technology. The microbubble structure was prepared by heating a hollow quartz tube with a fusion splicer. The temperature test range of this sensor is 20 °C–600 °C, the maximum test pressure is 1 MPa, the pressure sensitivity at 600 °C is 5.912 nm/MPa, and the temperature coefficient is approximately 0.17 pm/°C [5], as shown in Fig. 1(d).

## 2. Chemical Etching Technology

Fiber-optic Fabry-Perot pressure sensors fabricated using chemical etching technology typically employ hydrofluoric acid (HF) to etch the optical fiber, taking advantage of the high etchability of Si-based materials. This process is used to create microcavities that form the

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Fabry-Perot cavity structure. Guo et al. from the University of Massachusetts Lowell (USA) designed and fabricated an all-silica fiber-tip pressure sensor. A segment of multimode fiber was spliced onto a single-mode fiber, and then the optical fiber was immersed in HF acid, which etched a microcavity into the multimode fiber core. A 1.2 μm thick silica diaphragm was then thermally bonded to the fiber end face, thus forming a fiber-optic Fabry-Perot pressure sensor. The temperature test range of this sensor is 26 °C–43 °C, and the pressure test range is 6.9 kPa–48.3 kPa [6], as shown in Fig. 2(a) to 2(b). Simon et al. from the University of Maribor in Slovenia constructed two Fabry-Perot cavities on an optical fiber using HF etching processes to realize separate measurements of temperature and pressure. The temperature measurement range is 20 °C–80 °C, and the pressure measurement range is 0 Bar–1.4 Bar [7]. Chen et al. from China Jiliang University fabricated a fiber-tip Fabry-Perot pressure sensor by etching a microcavity on the end face of a multimode fiber using HF acid, and then filling it with UV-curable adhesive. The pressure sensitivity of this sensor is 40.94 nm/MPa, the temperature cross-sensitivity coefficient is 5.2 kPa/°C, the pressure measurement range is 0 MPa–0.92 MPa, and the temperature measurement range is 30 °C–85 °C [8], as shown in Fig. 2(c).

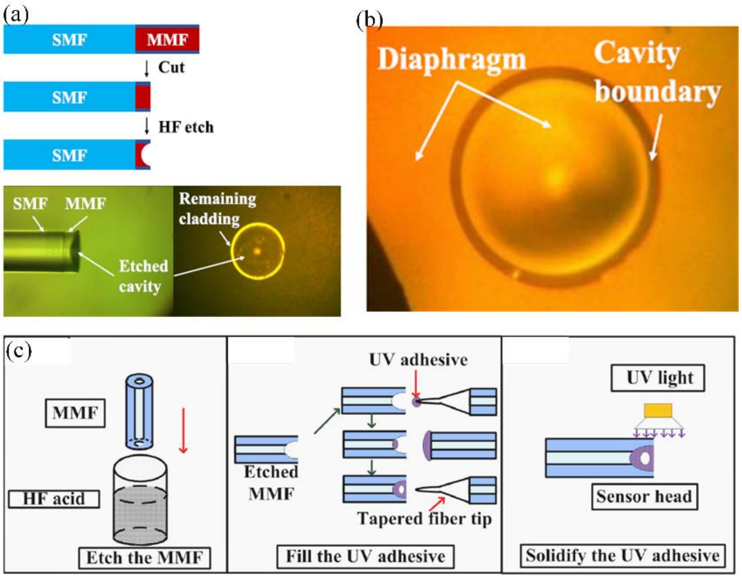


**Fig. 2** (a)–(c) Optic-fiber FP pressure sensor fabricated by chemical etching technology.

## 3. Laser Processing Technology

The development of laser technologies such as femtosecond laser technology provides technical support for the precise fabrication of micro-devices with true three-dimensional structures. The high-intensity laser pulses emitted by femtosecond lasers can ablate most solid materials with high surface quality or alter their internal refractive index. Due to the extremely high peak power and the fact that the pulse duration is shorter than the thermal diffusion time, femtosecond laser pulses produce almost no thermal damage during the machining process.

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Because of the multiphoton interaction nature, the ablation process can take place both on the material surface and inside the bulk of the material. Femtosecond lasers have already been successfully used to fabricate micro-channels and micro-cavities in glass materials. When performing microstructuring on optical fibers using femtosecond lasers, as long as the energy absorbed by the fiber material is sufficient, specific structures can be formed on the fiber, and the refractive index of the fiber core can also be modulated. Other laser processing technologies, such as $CO_2$ laser processing and excimer laser processing [9], can also be used to process optical fibers and other quartz-based materials. In China, several institutions have conducted research on laser micromachining of optical fibers, including Beijing Institute of Technology [10–12], Guangdong Ocean University [13–15], University of Electronic Science and Technology of China [16–18], Shenzhen University [19], and Nankai University [20].

Wang et al. from Nankai University in Tianjin proposed a highly sensitive fiber-optic Fabry-Perot pressure sensor based on the Vernier effect. The sensor is composed of a single-mode fiber, a hollow quartz tube, and another single-mode fiber. A micro-hole was fabricated on the sidewall of the hollow quartz tube using a $CO_2$ laser drilling method. The pressure sensitivity of the sensor is 80.3 pm/kPa, and the temperature test range is 25 °C–65 °C [20], as shown in Fig. 3(a). Tian et al. from Guangdong Ocean University proposed an all-quartz fiber-optic Fabry-Perot pressure sensor. This sensor was fabricated by $CO_2$ laser welding of a quartz fiber and a quartz diaphragm. The pressure test range is 0 kPa–3 kPa, and the temperature test range is 26 °C–77 °C [21], as shown in Fig. 3(b). Rao et al. from the University of Electronic Science and Technology of China proposed a Fabry-Perot pressure sensor for high-temperature dynamic pressure testing in internal combustion engines. The pressure-sensitive structure of the sensor was fabricated using laser processing technology. The temperature test range of the sensor is 40 °C–200 °C, with a repeatability accuracy of less than 0.8% [16], as shown in Fig. 3(c). Subsequently, Rao et al. integrated the aforementioned Fabry-Perot structure with a fiber Bragg grating to develop a fiber-optic Fabry-Perot sensor for multi-parameter measurement of strain/pressure under high-temperature environments [18]. Xiao et al. from Missouri University of Science and Technology in the United States fabricated a fiber-optic Fabry-Perot pressure sensor by using femtosecond laser to machine a thinned and roughened sensitive diaphragm on the fiber end face. The temperature test range of this sensor is 50 °C–200 °C [22].

Zhang et al. from Beijing Institute of Technology proposed a diaphragm-free fiber-optic Fabry-Perot pressure sensor. This sensor was fabricated by splicing a single-mode fiber, a hollow-core fiber, and a coreless fiber. A micro-channel for gas flow was machined on the sidewall of the hollow-core fiber using femtosecond laser. The sensitivity of the sensor at room temperature is 1.8 μm/MPa, the pressure measurement range is 0 MPa–10 MPa, and the temperature measurement range is 25 °C–600 °C [10], as shown in Fig. 3(d). Subsequently, Jiang et al. from Beijing Institute of Technology proposed a fiber-optic Fabry-Perot pressure sensor composed of a three-layer structure consisting of a single-mode fiber, a hollow-core fiber, and another single-mode fiber. A micro-channel was machined on the hollow-core fiber using femtosecond laser, and the sensor achieved a test temperature of up to 1007 °C [11], as shown in Fig. 3(e).

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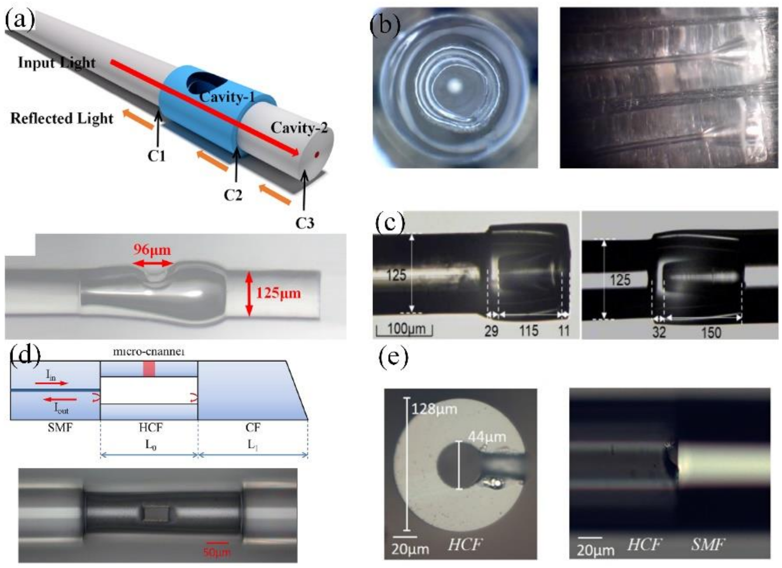


**Fig. 3** (a)–(e) Optic-fiber FP pressure sensor made by laser processing technology.

## 4. Fusion Splicing Technology

Fiber-optic Fabry-Perot pressure sensors fabricated by fusion splicing technology are primarily constructed by using a fiber fusion splicer to splice a section of fiber or hollow quartz tube onto an optical fiber to form a pressure-sensitive element. This fabrication method and sensor structure are simple; however, they are usually manufactured individually, making it difficult to ensure consistency among sensors.

Paulo et al. from the University of Aveiro in Portugal fabricated a fiber-optic Fabry-Perot pressure sensor by controlling the fusion splicing defects between two optical fibers. The maximum sensitivity of this sensor was 59.39 pm/kPa [23].

Sridhar et al. from Northeastern University in the United States developed a temperature-insensitive fiber-optic Fabry-Perot pressure sensor using offset fusion splicing technology. This sensor consists of a single-mode fiber and two segments of hollow fiber, with a pressure sensitivity of 4.314 nm/MPa, a maximum pressure test limit of 1000 kPa, and a maximum test temperature of 80 °C [23].

Peng et al. from Dalian University of Technology fabricated a fiber-optic Fabry-Perot pressure sensor for downhole pressure detection. A Fabry-Perot cavity was formed by splicing two ends of single-mode fiber to a section of hollow quartz, and two years of field testing were conducted in high-temperature oil wells. The test results demonstrated long-term stability of the sensor [25], as shown in Fig. 4(a). Zhao et al. from Qilu University of Technology used a hydrogen-oxygen flame to hermetically fuse a quartz capillary tube with an optical fiber to fabricate a fiber-optic Fabry-Perot pressure sensor for oil well pressure measurement. The test pressure reached up to 82 MPa, and the temperature test range was from room temperature to 175 °C [26], as shown in Fig. 4(b). Wang et al. developed a cascaded fiber sensor consisting of an FBG and a Fabry-Perot cavity to enable simultaneous measurement of temperature and pressure. The Fabry-Perot cavity was fabricated by inserting a single-mode fiber connected to an FBG and

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another fiber end into a hollow quartz tube, followed by fusion splicing. The maximum test pressure was 100 MPa [27], as shown in Fig. 4(c).

Xiong et al. from North University of China designed a diaphragm-free fiber-optic Fabry-Perot pressure sensor. The Fabry-Perot cavity was formed by inserting an FBG connected to a single-mode fiber and a hollow capillary tube into a hollow quartz sleeve and fusion splicing them together. The pressure test range of this sensor was 0.1 MPa–0.7 MPa, and the temperature test range was 20 °C–800 °C [28], as shown in Fig. 4(d). Jiang et al. from Beijing Institute of Technology fabricated a dual-cavity fiber-optic Fabry-Perot sensor by fusion splicing a segment of hollow fiber and photonic crystal fiber onto a single-mode fiber. The non-intrinsic Fabry-Perot cavity composed of hollow fiber was used for pressure measurement, while the intrinsic Fabry-Perot cavity composed of photonic crystal fiber was used for temperature measurement. The temperature test range was 40 °C–1000 °C, and the pressure test range was 0 MPa–10 MPa [29], as shown in Fig. 4(e). Domestic institutions that have also conducted research on this type of fiber-optic Fabry-Perot pressure sensor include Shenzhen University [30], Guangdong Ocean University [31], Hainan University [32], Wuhan University of Science and Technology [33], Northwest University [34, 35], China Jiliang University [36], Beijing Jiaotong University [37], Beihang University [38], Harbin Institute of Technology [39-41], among others.

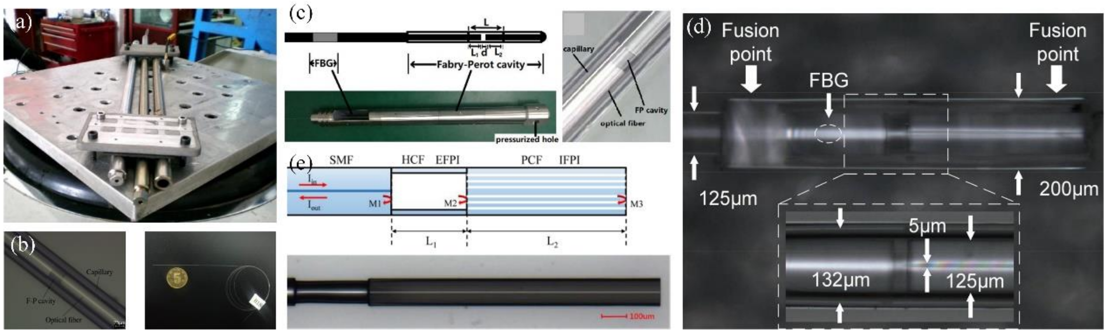


**Fig. 4** (a)-(e) Optic-fiber FP pressure sensor fabricated by fusion splicing technology.

## 5. Bonding Technology, 3D Printing Technology, and LTCC Technology

Fiber-optic sensors fabricated using bonding technology generally employ adhesives to construct the Fabry-Perot cavity in the sensitive components of the sensor. Commonly used adhesives include UV-curable glue and polymer-ceramic adhesives. Gao et al. from Xi'an Shiyou University proposed a fiber-optic Fabry-Perot multi-parameter sensor capable of simultaneously measuring pressure, temperature, and refractive index, based on single-mode fiber and UV-curable glue. The sensor consists of one FBG and three Fabry-Perot interferometers. The Fabry-Perot interferometers are fabricated using single-mode fiber, UV-curable glue, and integrated materials. The sensor processes the interference signal using a Fourier band-pass filter and fast Fourier transform, which allows the frequency of each

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individual Fabry-Perot cavity to be extracted freely. The pressure resolution is 6 kPa, and the temperature test range is 30 °C–70 °C [42], as shown in Fig. 5(a).

Bae et al. from Howard University fabricated a miniature diamond-based fiber-optic Fabry-Perot pressure sensor using dual polymer-ceramic adhesives. Within a pressure measurement range of 2.0 psi–9.5 psi, the pressure sensitivity is 18.5 nm/psi, and the operating temperature reaches up to 275 °C [43], as shown in Fig. 5(b).

Xiong et al. from North University of China fabricated a high-temperature fiber-optic Fabry-Perot pressure sensor using low-temperature co-fired ceramic (LTCC) technology. The Fabry-Perot interferometer is composed of a single-mode fiber and an alumina ceramic sensitive head fabricated using LTCC technology. The sensor's temperature test range is 20 °C–300 °C [44], as shown in Fig. 5(c). With the continuous development of 3D printing technology, it has also found applications in the field of fiber-optic sensing. By using 3D printing technology [45], it is possible to fabricate the three-dimensional structure of the sensitive units of fiber-optic sensors, offering a novel method for constructing fiber-optic sensors with special structures. Xiao et al. from Clemson University in the United States developed an all-glass fiber-optic Fabry-Perot pressure sensor using laser fusion-based 3D printed glass. The pressure test range is 0 kPa–500 kPa, the temperature test range is 20 °C–700 °C, and the temperature sensitivity is 0.215 nm/°C [45], as shown in Fig. 5(d).

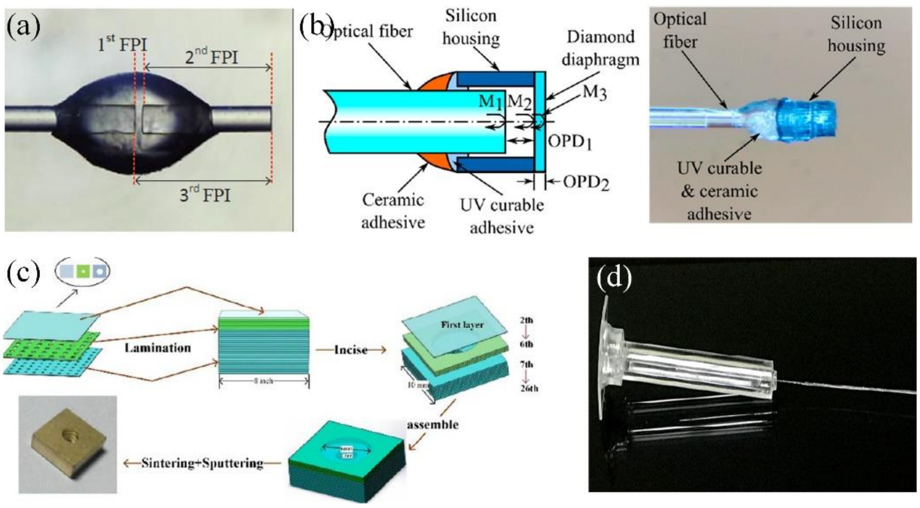


**Fig. 5** (a)-(b) Optic-fiber FP pressure sensor fabricated by bonding technology
(c) Optic-fiber FP pressure sensor fabricated by LTCC technology
(d) Optic-fiber FP pressure sensor fabricated by 3D printing technology

## 6. MEMS Technology

Compared with the aforementioned fabrication methods, MEMS technology offers the advantage of wafer-level production of fiber-optic Fabry-Perot pressure sensors, and can effectively ensure the consistency of sensor sensitive units while maintaining low processing

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costs. Therefore, many researchers have conducted related studies. Currently, materials commonly used in MEMS technology include Si [46-54], Pyrex glass [46-52], SiC [46], and sapphire [55-57]. Luna Innovations Inc. in the United States developed a high-temperature fiber-optic Fabry-Perot pressure sensor using Si-Pyrex anodic bonding. Through a special packaging structure, the test temperature reached 600 °C, as shown in Fig. 6(a); the company also fabricated a fiber-optic Fabry-Perot high-temperature pressure sensor integrating SiC and sapphire fiber, which can be used at even higher temperatures [46], as shown in Fig. 6(b). Wang et al. from Virginia Tech in the United States fabricated a sapphire fiber-optic Fabry-Perot high-temperature pressure sensor using reactive ion etching and direct wafer bonding, but only conducted pressure measurements ranging from 0.04 MPa to 1.38 MPa at room temperature [55]. Jia et al. from North University of China developed a high-temperature fiber-optic Fabry-Perot pressure sensor using Si-Pyrex anodic bonding. The sensor's testing temperature range was 20 °C–350 °C, and the pressure testing range was 0 MPa–0.5 MPa [47], as shown in Fig. 6(c). Yin et al. from Tianjin University developed a fiber-optic Fabry-Perot pressure sensor capable of simultaneously measuring temperature and pressure by using Si-Pyrex anodic bonding and bonding the signal transmission fiber with the sensitive unit using adhesive. The sensor's testing temperature was 20 °C–70 °C [48], as shown in Fig. 6(d); Liu et al. from Tianjin University also developed a fiber-optic Fabry-Perot pressure sensor using Si-Si direct bonding and high-temperature adhesive. The maximum test temperature reached 700 °C, with a temperature drift coefficient of 0.197 nm/°C [58].

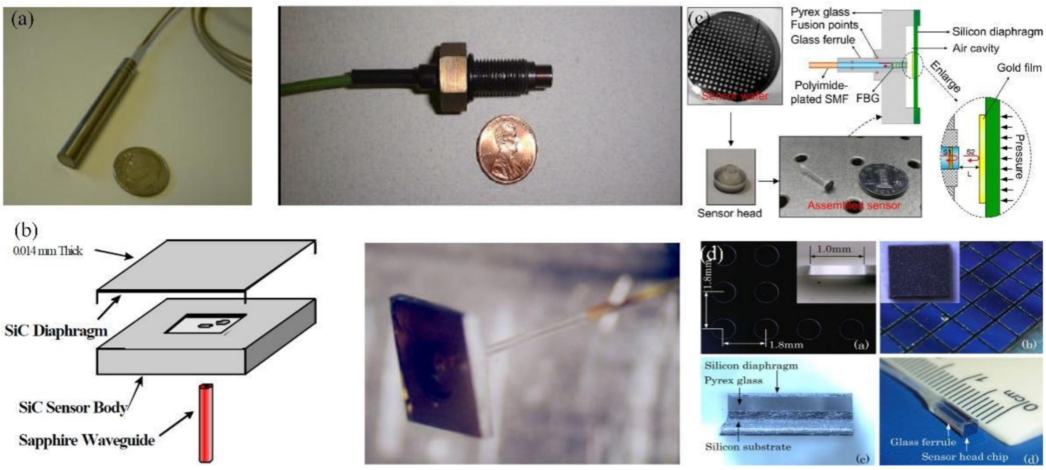


**Fig. 6** (a)-(b) Optic-fiber FP pressure sensor based on Si and SiC developed by Luna Company (c) Optic-fiber FP pressure sensor developed by North University of China (d) Optic-fiber FP pressure sensor developed by Tianjin University.

## 7. Conclusion

By analyzing the current research status of fiber-optic Fabry-Perot pressure sensors, we can understand that from the perspective of practical applications, traditional fiber-optic Fabry-Perot pressure sensors suffer from issues such as reproducibility, repeatability, and long-term

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stability under high-temperature and harsh environments. Fiber-optic Fabry-Perot sensors fabricated using arc discharge technology, chemical etching technology, laser technology, fusion splicing technology, bonding technology, 3D printing technology, and LTCC technology are usually made individually. Due to limitations in fabrication processes, it is difficult to ensure the consistency of the sensor's sensitive units, which restricts their engineering applications. On the other hand, MEMS technology can solve the above-mentioned consistency issues. However, since MEMS fabrication processes based on Si wafers are currently very mature, Si wafers and Pyrex materials are typically used to fabricate wafer-level fiber-optic Fabry-Perot pressure sensors. Due to the intrinsic temperature tolerance limitations of Si materials, it is difficult for such sensors to maintain stability in high-temperature environments exceeding 350 °C. Moreover, problems such as thermal stress mismatch of the sensor's sensitive units under high-temperature conditions (for example, when using different materials to fabricate the sensitive unit or using adhesives to bond the sensitive unit to the optical fiber) also limit their applications in high-temperature environments. Therefore, it is of great significance to develop a wafer-level manufacturable, thermally stress-matched, highly consistent and high-temperature-resistant fiber-optic Fabry-Perot pressure sensor.

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