

REVIEW

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Fiber optic sensing technologies potentially applicable for hypersonic wind tunnel harsh environments



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Abstract

Advanced sensing techniques are in big demand for applications in hypersonic wind tunnel harsh environments, such as aero(thermo)dynamics measurements, thermal protection of aircraft structures, air-breathing propulsion, light-weighted and high-strength materials, etc. In comparison with traditional electromechanical or electronic sensors, the fiber optic sensors have relatively high potential to work in hypersonic wind tunnel, due to the capability of responding to a wide variety of parameters, high resolution, miniature size, high resistant to electromagnetic and radio frequency interferences, and multiplexing, and so on. This article has classified and summarized the research status and the representative achievement on the fiber optic sensing technologies, giving special attention to the summary of research status on the popular Fabry-Perot interferometric, fiber Bragg gratings and (quasi) distributed fiber optic sensors working in hypersonic wind tunnel environment, and discussed the current problems in special optical fiber sensing technologies. This article would be regarded as reference for the researchers in hypersonic wind tunnel experiment field.

Keywords: Fiber optic sensor, Hypersonic wind tunnel, Harsh environment, Fiber optic force balance, High temperature strain sensing, High temperature sensing, Distributed sensing

1 Introduction

Since the 1960s, the optoelectronic techniques have been developed at a rapid pace, especially the semiconductor lasers and the optical fiber technologies, during which it is found that light wave not only could be transmitted with the optical fiber, but also could have its characteristic parameters modulated by outside physical quantities. As sensing elements, the optical fiber is able to detect multiple physical quantities. Thus, based on the various sensing principles of optical fiber, quite a few of technical solutions have been put forwards and gradually evolve into a new sensing measurement technology - optical fiber sensing technology. Fiber optic sensors have become a focus in the field of sensing technologies by right of their many advantages such as compact,

light-weighted, high sensitivity, high multiplexing, anti-electromagnetic interference and easy to be embedded into material.

At the early stage, the intensity - modulated type fiber optic sensors took the lead of optical fiber sensing technologies [1]. Since the 1980s, the interference fiber sensors have gained the extensive attention of researchers, with interference fiber optic gyro, fiber optic hydrophone and fiber optic current transformer as representatives [2–6], and promoted the development of related optoelectronic devices. By the end of the 1980s, with the invention of fiber Bragg gratings (FBG), FBG optical fiber sensing technology has become the research focus, and meanwhile, the interference fiber optic sensing technology gets mature step by step. After 2000, the gradually matured optoelectronic elements and signal processing technologies provide researchers with how to apply various sensors, such as Fabry-Perot Interferometric (FPI) fiber optic sensors, FBG sensors, distributed fiber optic sensors, to different engineering application areas. Fiber optic sensor systems with very quick response are becoming available, with read-out frequencies over 100 kHz, enabling the fiber optic sensors to operate as both static and dynamic loading sensors. This means that the fiber optic sensors enter into a practical stage. Following the development of optical fiber communication industry, the optical fiber sensing technologies become another major industry of optoelectronic technologies [7]. Among them, what are popular, in-depth researched and most promising sensors are the FPI fiber optic sensors, the FBG fiber optic sensors and the (quasi) distributed sensors based on fibers, applying to the health detection, the petrochemical engineering and the energy & power in terms of aviation, spaceflight and large building structure. All in all, the fiber optic sensors meet the features below:

- (1) Compact, light weighted and low power consumption. In general, the fiber optic sensors have complicated process technologies involving the semiconductor process, laser processing, precision machining and forming technologies, so as to make sensors smaller or more miniature. Thus, traditional bulk optic components such as beam splitters, combiners, and objective lenses have been rapidly replaced by small-sized fiber devices that enable the sensors to operate on fiber scales, typically 125 μm in diameter. Besides, the data carrying bandwidth of fiber optics is so high that hundreds and potentially thousands of sensors can be supported by a single fiber. Fiber optic sensing system could reduce their power consumption to several Watt level, by adopting the power supply with high electro-optical conversion efficiency, refrigerating efficiency and the modulator with low driven voltage.
- (2) Adaptation to application requirements in harsh environments. In general, the environment where the fiber optic sensors are used is relatively severe. For example, to name a few, in space launch applications, the fiber optic sensors are required to survive under high impact force (peak acceleration up to 1000 g) and/or high frequency vibration (1000~5000 Hz) [8]; Electricity industry requires that the fiber optic sensors have high insulativity; Oil drilling and geological exploration industries require that the sensors are resistant to high temperature (up to 350 $^{\circ}\text{C}$) and pressure (up to 60 MPa) [9]; Nuclear power stations require that the sensors are highly resistant to radiation.
- (3) Reliability and long life span. For example, in some military fields, the sensors have to be very reliable to work and store for a long time, normally more than 10 years

or even 20 years. In some fields (such as satellite and electricity plant), optoelectronic elements are required to work continuously for an even longer time.

In comparison with traditional electromechanical or electronic sensors, the fiber optic sensors have relatively high potential to work in hypersonic wind tunnel [10]. Hypersonic wind tunnel experiment technologies are involved to many subjects such as aerodynamic forces, aerothermodynamics, thermal protection of aircraft structures, heat-fluid-solid coupling, hypersonic boundary layer, air-breathing propulsion system and light-weighted and high-strength material, and so on. This article has classified and summarized the research status and the representative achievement on the fiber optic sensing technologies, giving special attention to the summary of research status at home and abroad on the popular FPI, FBG and (quasi) distributed fiber optic sensors working in hypersonic wind tunnel environment, and discussed the current problems in special optical fiber sensing technologies. Therefore, this article would be regarded as reference for the researchers in this field.

2 Working principle of fiber optic sensors

2.1 Fabry-Perot Interferometric (FPI) fiber optic sensor

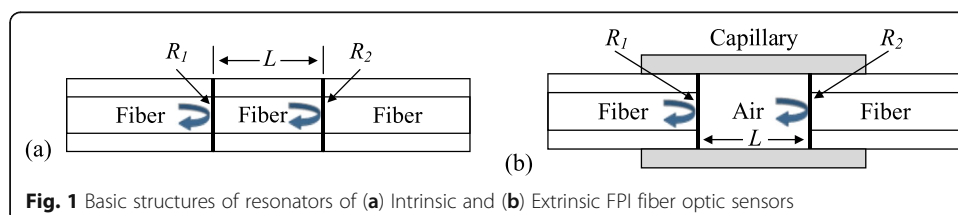
The FPI fiber optic sensors could be classified into Intrinsic Fabry-Perot Interferometric (IFPI) fiber optic sensors and Extrinsic Fabry-Perot Interferometric (EFPI) fiber optic sensors [11, 12] according to their structures. The inside of IFPI fiber optic sensor consists of a section of optical fiber and two mirrors at both ends of this fiber, as shown in Fig. 1a. The resonator inside of EFPI fiber optic sensor consists of two mirrors and air in between, as shown in Fig. 1b. The mirror in FPI fiber optic sensor normally has low reflectivity. The Fresnel reflection is about $R \approx 4.0\%$ between the end face of fiber and the air, and the backwards-reflected light is also measured. Therefore, the detected interference signal is approximately equal to the cosine type signal of two-beam interference.

With excessive loss neglected, the intensity I_r of reflected light from FPI sensor is dependent on the distance L between the two reflecting surfaces, according to Airy function [13]:

$$I_r = \frac{4R \sin^2(2\pi L/\lambda)}{(1-R)^2 + 4R \sin^2(2\pi L/\lambda)} I_i, \tag{1}$$

where R is the reflectivity of the mirrors, and λ and I_i are the wavelength and intensity of incident light, respectively.

The beam of light source is propagated to the FP cavity along the lead-in / lead-out fiber, among which a fraction of incident light is reflected on the end face of lead-in/ lead-out fiber, forming the first reference beam with the optical intensity $I_{1r} \approx 4\%I_i$



arising from reflectivity $R \approx 4\%$. Most transmitted light goes through the FP cavity and then is reflected back, creating the second reference beam ($I_{2r} \approx 3.69\%I_i$). Reflected for three times, the light intensity $I_{3r}(\approx 0.15\%I_i)$ is much lower than that of the first one, so the effect of I_{3r} could be neglected. This means that, it is enough to consider only two reflected beams. Thus, the intensity of reflected light in Eq. (1) could be simplified to [14]

$$I_r = 2R \left[1 - \cos\left(\frac{4\pi L}{\lambda}\right) \right] I_i. \tag{2}$$

For FPI fiber optic sensor, the reflected light spectrum curve, as well as the fitting based on Eq. (2), is shown in Fig. 2.

As for FPI fiber optic sensor, the wave length of reflection interference light λ is mainly dependent on the elasto-optical effect and the thermo-optical effect, with equation shown below [14]:

$$\lambda = \lambda_{initial} + \Delta\lambda_L + \Delta\lambda_T, \tag{3}$$

where:

$$\Delta\lambda_L = 2L\varepsilon, \tag{4}$$

$$\Delta\lambda_T = n \frac{L \Delta T}{\lambda \Delta L}, \tag{5}$$

$\lambda_{initial}$ is the original wavelength; ε , n , ΔL and ΔT are strain, fiber reflectivity, change in cavity length and change in temperature, respectively.

Equations above represent that FPI fiber optic sensors can be used for multiple parameters sensing, such as temperature, strain and pressure. As FPI fiber optic sensors make use of change in cavity length to pick up the outside parameters, the length of sensing element is dependent on the actual operating requirements, ranging from a few

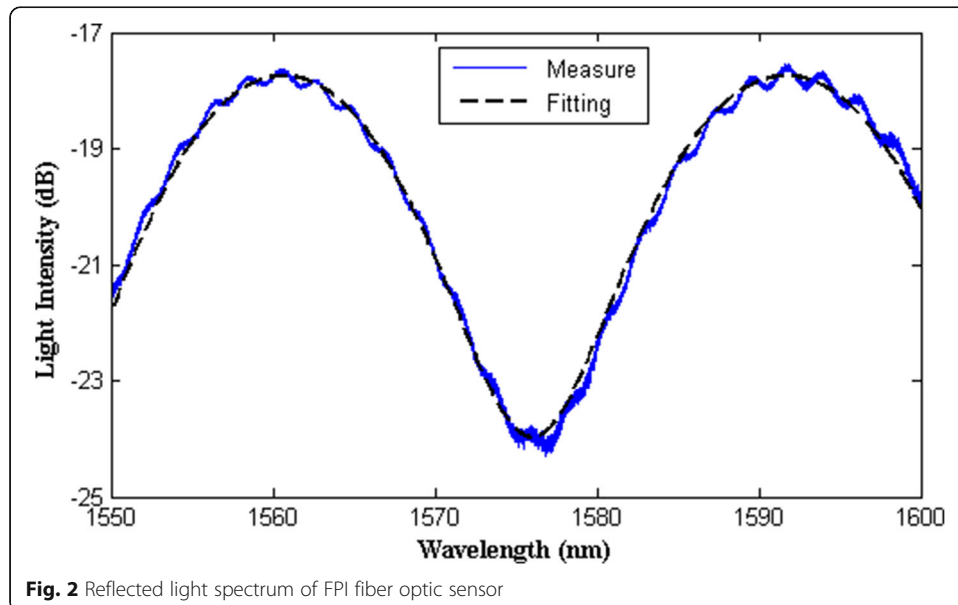


Fig. 2 Reflected light spectrum of FPI fiber optic sensor

to hundreds of micrometers, able to satisfy different measurement requirements such as high spatial resolution, miniaturization and high sensitivity.

In 1988, Lee, Talyor and others reported on IFPI-based fiber optic sensors [6]. In 1991, Murphy and others reported EFPI strain fiber optic sensors that tested the fatigue property of F15 fighter fuselage by inserting the fiber into a quasi-straight capillary tube and then attaching them onto the fuselage with epoxy resin [5, 15]. In the same year, Wolthuis used silicon diaphragm as a mirror and a pressure-sensing element, generating EFPI fiber pressure and temperature sensor suitable for medical field [16]. Since 2000, researchers have developed multiple FPI fiber optic sensors by adopting laser welding, arc welding, micro-machining and others, making the FPI fiber optic sensors more reliable and stable for a long time. Up to now, FPI fiber optic sensors have been widely adopted to measure the pressure, temperature and strain under such severe conditions as oil wells, the dynamic pressure in gas turbine engine and transformer with high voltage and power, and the pressure of element implanted in human body and others [7, 17].

Since the beginning of the 1990s, universities and research institutes in China have started the study on FPI fiber optic sensors, and many of them have been applied to the fields of bridges and oil wells for strain/pressure measurements [18, 19]. Dalian University of Technology has developed a sensing system combining the FPI based pressure sensor [20, 21] with the distributed temperature sensor, which can reach 0.1% accuracy for the pressure measurement with a 0–30 MPa working range and 1 °C accuracy for the temperature measurement in a working range from room temperature to 300 °C; additionally, a resolution of below 1.4 kPa for the pressure measurement and 0.5 °C for the temperature measurement has been realized. And this sensing system has now been successfully applied in Liaohe and Xinjiang oil wells. Ding etc. at Beijing Institute of Technology [22] demonstrated a miniature fiber-optic sensor working up to 500 °C. Rao etc. at University of Electronic Science and Technology of China [23, 24] fabricated an all-fiber in-line FPI strain sensor working over a temperature range from 20 °C to 800 °C by using 157-nm laser micromachining, and linearity and repeatability of the sensor were ~ 99.92% and ~ ± 0.8 μe over 500 μm displacement.

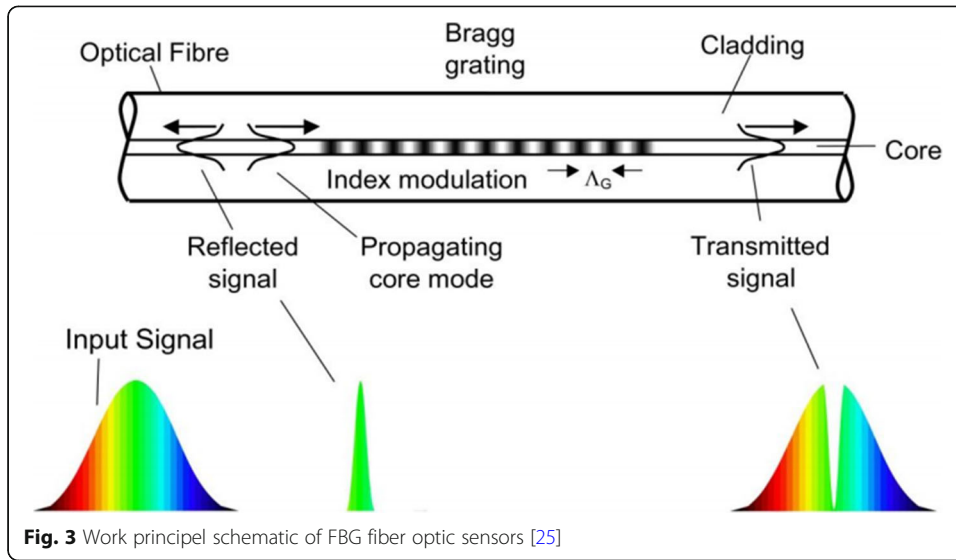
2.2 Fiber Bragg Grating (FBG) fiber optic sensors

FBG is one of the optic fiber passive elements rapidly developed in recent years. Using the photo-sensitivity of optic fiber (the outside incident photon and the germanium ion interact with each other, leading to refractive index changed permanently), the FBG establishes a spacious phase grating inside of fiber core, of which period and modulation amplitude of refractive index are constants [18] (Fig. 3), with the grating period normally less than 1 μm and the refractive index of fiber core changing in accordance with equation below:

$$\Delta n(z) = \bar{\delta n} \left[1 + \nu \cos\left(\frac{2\pi}{\Lambda} z\right) \right], \quad (6)$$

where $\bar{\delta n}$ is the average growth value of refractive index of fiber core, ν is the modulation coefficient of refractive index ($0 \leq \nu \leq 1$), Λ is the period of uniform grating, and z is the position coordinate of fiber grating in the axial direction.

If the phase-matching conditions are satisfied, the Bragg wave length of grating is



$$\lambda_B = 2n_{eff}\Lambda, \tag{7}$$

where λ_B is the Bragg wavelength and n_{eff} is the effective refractive index of optical fiber.

As one of the reflective filters with fine performance, Bragg grating has reflectivity as high as approximately 100%, with its reflection bandwidth and reflectivity flexibly controlled by changing the writing conditions so as to meet the needing. In addition, the reflected light center wavelength varies with the outside temperature and pressure, with the relationship between the changing quantity and temperature and strain shown below [25]

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha_f + \xi)\Delta T + (1-P_c)\Delta\varepsilon, \tag{8}$$

where $\alpha_f = \frac{1}{\lambda} \frac{d\lambda}{dT}$ is the coefficient of thermal expansion of optical fiber, $\xi = \frac{1}{n} \frac{dn}{dT}$ is the thermal-optical coefficient of optical fiber and $P_c = -\frac{1}{n} \frac{dn}{d\varepsilon}$ is the elasto-optical coefficient of optical fiber.

With corresponding sensing structure, FBG fiber optic sensors could measure various parameters such as temperature, strain and pressure. The wavelength in the middle of reflected spectrum of fiber grating is called as peak wavelength, as the reflected spectrum of fiber grating is symmetrical, with the maximum reflectivity at center wavelength. In addition, strain and temperature could drift the wavelength of fiber grating. In other words, the higher the temperature of the strain becomes, the bigger the center wavelength is. As for the fiber grating working in 1550 nm of band, the center wavelength has the temperature coefficient of approximately 10 pm/°C and the strain coefficient of about 1.2 pm/με.

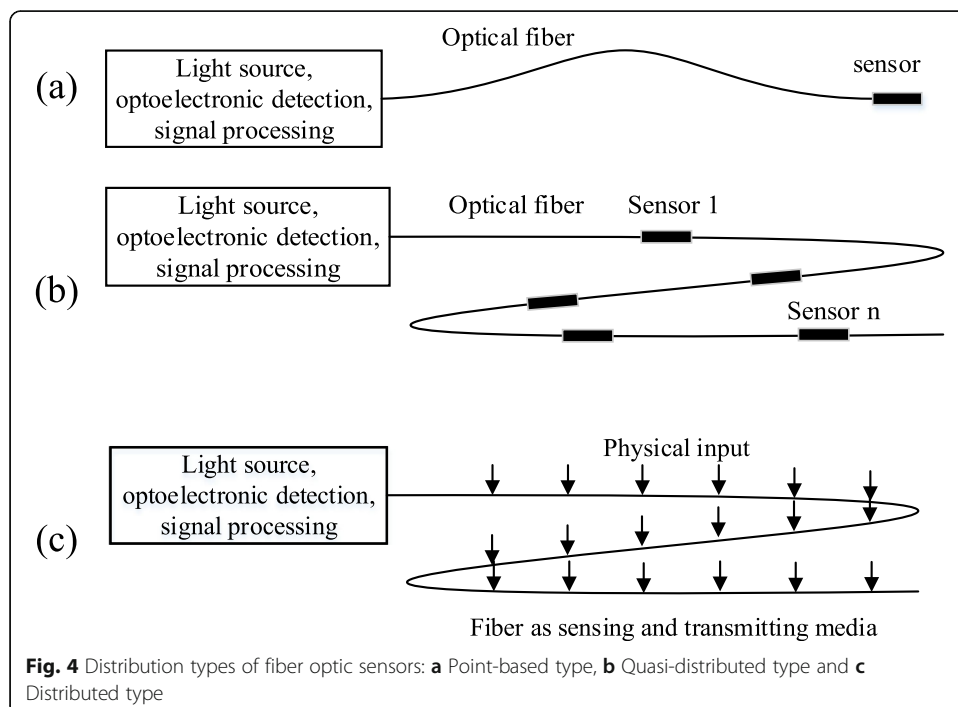
In 1978, Hill and others from Communications Research Center Canada achieved the backward -mode coupling FBG [26] in the way that the bi-directional 488 nm argon ion laser created a standing wave in the germanium-containing fiber through interference, allowing the fiber refractive index to alter periodically along the axial direction. But, due to the limitation of writing method and optical fiber development, Hill grating

was at low efficiency to prepare and relatively poor in spectrum features. In 1989, Meltz and others adopted 244 nm UV-light dual-beam holographic exposure technologies to develop FBG [27], providing a practical method to make the FBG. In 1989, while fiber grating technology was being developed to be written on the side of UV light, Morey and others were the first to study the fiber grating temperature and strain sensing features, finding out the center wavelength of fiber grating has good linear relationship with temperature and strain [28]. In 1993, Bell Labs put forward the hydrogen-carrier technique to increase the fiber sensitivity to light [29]. In the same year, Hill also came up with the phase shift mask method to produce the fiber grating [30], which is the most popular way up to now.

Since the early 1990s, FBG sensing technology has been developed in several universities in China, such as Tsinghua University, Chongqing University, Wuhan University of Technology, Harbin Institute of Technology, Tianjin University, Chinese Academy of Sciences and so on. FBG sensors have been applied in many fields, like bridge health monitoring, high temperature and high pressure sensing in oil well and seismic detection [31–34]. Besides, Liu etc. at Shanghai Jiao Tong University demonstrated an ultra-high resolution FBG strain sensor with a broad frequency range from quasi-static to several hundred hertz, and the sampling rate is up to 500 samples/s, with a strain resolution better than 0.01 ne and dynamic range of 149 dB at 10 Hz [35].

2.3 (Quasi) distributed optical fiber sensing technology

In accordance with the distribution of parameters to be measured, fiber optic sensors are classified into point-based, quasi-distributed and distributed fiber optic sensors. As shown in Fig. 4a, point-based fiber optic sensor has each fiber connected with merely one fiber optic sensor, with sensitive area much less than the length of fiber. For



example: the above-mentioned FPI and FBG belong to this kind of sensor. As shown in Fig. 4b, the quasi-distributed fiber optic sensor has each fiber connected with multiple point-based optic fiber sensors, sensing and measuring the parameters at several positions on fiber path. For example: fiber grating sensing matrix [36] and fiber hydrophone matrix [37]. As shown in Fig. 4c, the distributed fiber optic sensor not only has the sensing functions, but also transmits the optical wave signal, picking up the outside parameters continuously arranged along the fiber path. For example: distributed fiber Raman temperature sensor [38] and fiber Brillouin temperature / strain sensor [39].

Using of inhomogeneity of the constituent in fiber, the distributed fiber optic sensor could have its refractive index non-uniform in the microcosmic way, featuring long sensing length, simple structure, convenience and high performance cost ratio. As short pulse emitted by the pulsed laser is transmitting in fiber, the change in features (frequency, light intensity and polarization state) of backward scattered light could determine the value of physical quantity to be measured, and the duration of echo could determine the position. The scattering mechanisms used for engineering include Rayleigh scattering [40], Raman scattering [41] and Brillouin scattering [42]. Now, it becomes relatively mature that the distributed fiber optic sensing system is with a spatial resolution of 1 m at least (<http://www.sensornet.co.uk>, <http://www.omnisens.com>, <http://www.neubrex.com>, <http://www.ozopics.com>). Furthermore, OZ Optics Company in Canada and Neubrex Company in Japan have made the trial sample with 10 cm spatial resolution [43].

The quasi-distributed fiber optic sensor has a series of FBG point-based sensors laid on one single fiber, increasing the spatial resolution that is normally less than 1 cm or even dozens of micrometers. The quasi-distributed fiber optic sensors have other advantages: generating very strong light signal and providing very high signal to noise ratio. Therefore, this kind of sensors could obtain higher measuring precision and resolution than the distributed fiber optic sensors. As for the quasi-distributed fiber optic sensors based on FBG (principle shown in Fig. 5), the normal multiplexing technologies are classified into wavelength division multiplexing (WDM) [44] and time division multiplexing (TDM) [45]. In addition, the quasi-distributed fiber optic sensors are highly potential to precisely measure the stress/strain, temperature and others on the model surfaces under hypersonic wind tunnel conditions, because they are highly sensitive to the temperature, strain/stress, vibration and other outside physical quantities,

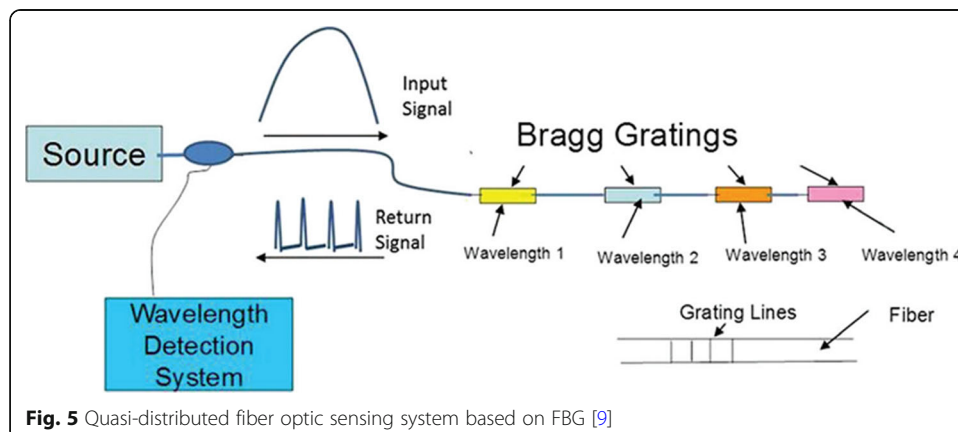


Fig. 5 Quasi-distributed fiber optic sensing system based on FBG [9]

compact, wide dynamic zone, reliable and strong multiplexing capacity of quasi-distribution.

Domestic research in the field of (quasi) distributed optical fiber sensing has also made considerable progress. Rao et al. at University of Electronic Science and Technology of China demonstrated an ultra-long-distance distributed sensing system, and the sensing distance was up to 154.4 km with 5 m spatial resolution and $\pm 1.4^\circ\text{C}$ temperature uncertainty [46]. Dong et al. at Harbin Institute of Technology developed a distributed temperature sensor, with 2 cm spatial-resolution hot-spot detection and 2°C temperature accuracy over a 2 km sensing fiber [47]. Ding et al. at Tianjin University constructed a distributed vibration sensor that can have a dynamic range of 12 km and a measurable vibration frequency up to 2 kHz with a spatial resolution of 5 m [48]. Meanwhile, Fan et al. at Shanghai Jiao Tong University developed a distributed vibration sensor that has a measurement range of 40 km, a spatial resolution of 3.5 m, a measurable vibration frequency up to 600 Hz, and a minimal measurable vibration acceleration of 0.08 g [49]. Zhang et al. at Chinese Academy of Sciences developed an optical reflectometry, and the reflection events can be precisely located in a detection range of ~ 47 km with a range-independent resolution of 2.6 mm [50]. Jiang et al. at Wuhan University of Technology developed large-scale FBG arrays made with in-line FBG fabrication, and obtained the reflection spectra of an ultra-weak FBG array with near-identical 3010 FBGs, using a wavelength scanning time division multiplexing scheme [51].

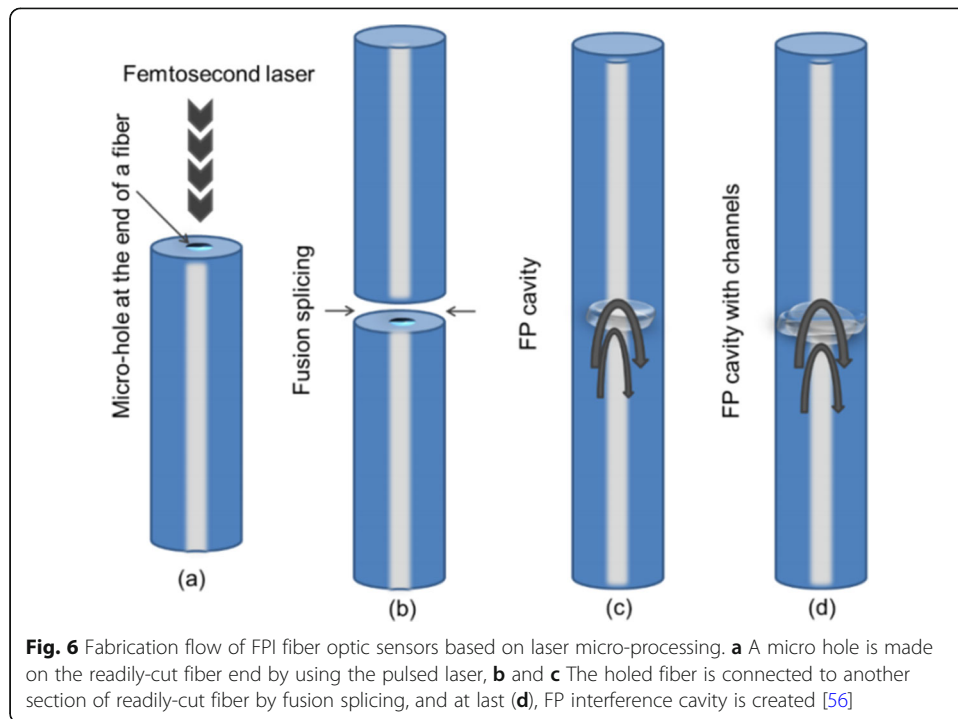
3 Fabrication process of fiber optic sensor

With the development of fiber optic sensor, the fabrication process of sensor is a fundamental step to develop the fiber sensor. Besides, the rapid development of miniaturization process provides a new way to fabricate the new generation of miniaturized fiber sensors, as well as a chance for fiber optic sensors to work under harsh environments.

3.1 FPI fiber optic sensors

This kind of sensors has not yet batch developed, because traditional micromachining process is very difficult to directly produce on micro-structure of fiber, and accordingly very expensive. The laser miniaturization process, micro / nano fabrication and film technology push the research on new generation of optoelectronic elements (optical communication devices, fiber sensors and electric sensors) by providing the new technical means [52–54]. For example, Rao and others [14, 55, 56] have fabricated FPI sensors based on 157 nm laser micro-machining process, and the reliability of the sensor could be guaranteed by decreasing the size of sensors and adopting the full-quartz structure, with the process flow shown in Fig. 6.

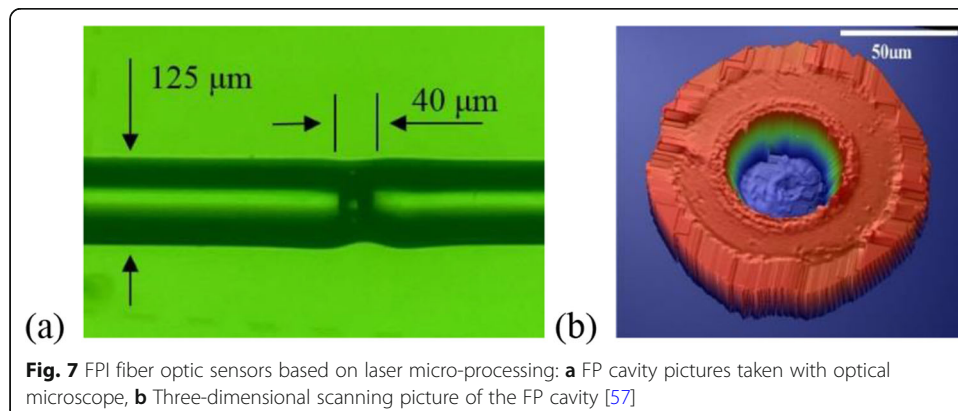
Figure 7 shows the FPI fiber optic sensors made with this method [57]: two reflectors are parallel with each other and the outside surfaces are well spliced together. Scanned with profilometer, FP cavity respectively has the average roughness of 135 nm and the root-mean-square value of roughness of 205 nm (R_a and R_q), proving that the reflector on the end of fiber is similar to a mirror.

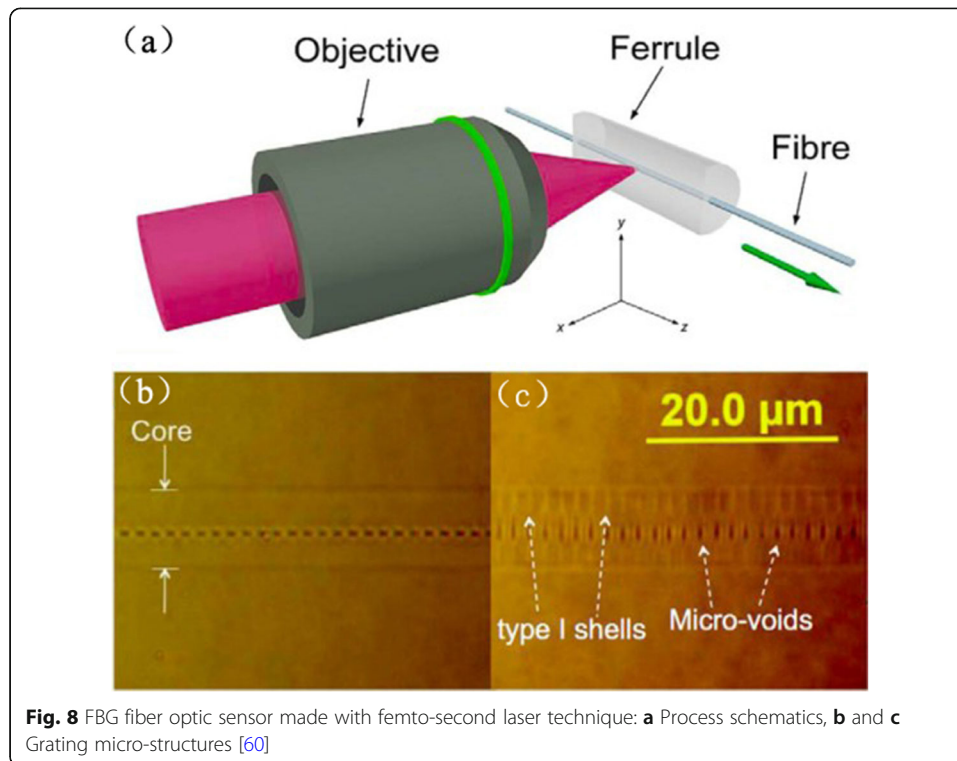


3.2 FBG fiber optic sensors

Based on the light sensitivity of fiber, the grating could be written into almost all kinds of fibers by adopting proper light source and sensitization technologies. There are many ways to fabricate the fiber grating, mainly two-beam interference method, phase mask method and point-by-point writing method [58, 59]. Among them, the phase mask is the most effective and popular way to fabricate the gratings up to now. By using process with femto-second laser technique, the FBG could work normally at severe conditions such as high temperature, high voltage and high ionizing radiation.

The femto-second laser pulse in transparent glass could induce the permanent change of refractive index of fiber, because when the ultra-short pulse with super-high peak power density is focused on the glass, the instantaneous high energy deposition in the focus zone could induce the breakage of molecular bond due to the multi-photon absorption and the extremely-high non-linear effect, forming the locally traumatic



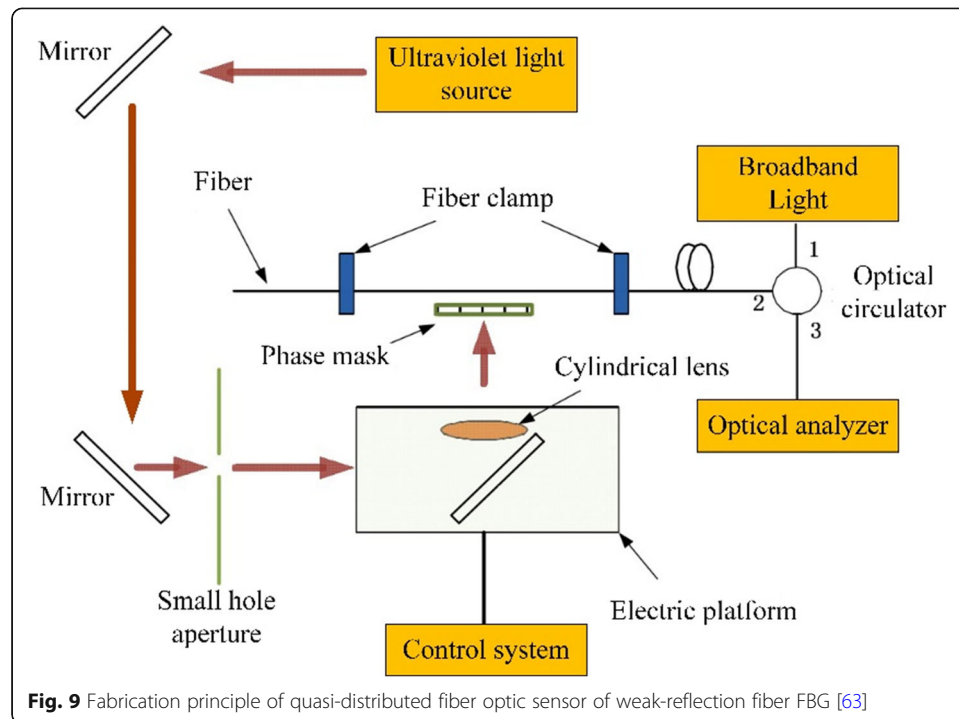


change in refractive index. Schematic of typical writing device and micro structure of grating are shown in Fig. 8 [60].

Many studies show that FBG by adopting femto-second laser technologies is not only limited to the quartz fiber, but also used for special waveguide and non-linear crystal fiber that cannot be realized by UV phase mask technique. For example, the sapphire single-crystal fiber FBG [61] fabricated by D. Grobnc and others could have the temperature stabilized at as high as 1500 °C; the full quartz photonic bandgap fiber Bragg grating made by Yuhua Li and others could keep the temperature at 700 °C [62].

3.3 Quasi-distributed fiber optic sensors based on FBG

In order to realize the quasi-distributed fiber optic sensor with large capacity, high density and long distance sensing, and also to put it into practical use by reducing the fabrication cost, the phase mask technique is normally used to repeatedly and online write on the single weak reflective fiber, guaranteeing that the weak-reflection FBG written on the single fiber has the same center wavelength, the reflectivity and bandwidth. With the fabrication principle shown in Fig. 9 [63], this system is composed of laser source, optical system, control system and detection system. Three total-reflection mirrors could adjust the output direction of UV. Then two beams interfere with each other, forming bright and dark strips and modulating the refractive index of the optical fiber core under the corresponding light intensity. During fabrication, the photosensitive fiber is fixed and adjusted with two fiber clamps, so that all the weak-reflection FBG could be written on the single fiber.

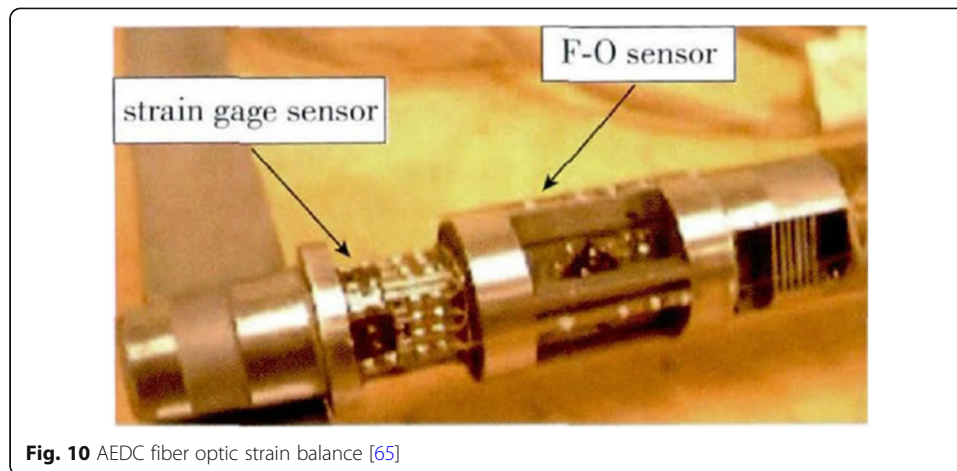


4 Potential applications in hypersonic wind tunnel environments

4.1 Fiber optic strain balance

The fiber optic strain balances based on fiber optic sensors are newly developed to adapt to the aerodynamic experiment under severe plasma and electromagnetic conditions. At present, the metal resistor strain balances are normally used to measure aerodynamic forces. Over the years, metal resistor strain balances have been developed to a fairly high level, strongly supporting the researches on aerodynamic experiments. However, various wind tunnel experiments have higher requirements on the accuracy of aerodynamic data under harsh environment. In such case, the regular metal resistor strain balance would hardly meet the severe requirement. Just as Dr. Ulrich Jansen said, “the potential to increase the quality of balance data is quite low. We have to place our hope on the new technique of balance, instead of the further optimization of current balance technologies” [64]. Fiber optic sensors bring new thoughts for aerodynamic force measurement because of their high sensitivity, reliability, resistance to electromagnetic interference, corrosion and high-temperature environment.

At present, fiber optic strain balances have two main types: one type of such balance is based on FPI fiber optic sensors, which Arnold Engineering Development Center (AEDC) made a lot effort to design and research [65, 66], results showing that fiber optic balances (as shown in Fig. 10) have higher accuracy and anti-interference capacity than the traditional metal resistor stain balance. Based on this principle, China Aerodynamics Research and Development Center (CARDC) developed a prototype of multi-component fiber optic balance [57, 67], as shown in Fig. 11. The strain sensitivity of the FPI sensor was about $0.135\mu\epsilon$, and it has been calibrated and evaluated in both Ma4 and Ma8 hypersonic flows. The static calibration accuracy of the FPI balance is better than 0.5% at full scale design load rang, and good repeatability (better than 1.0%) of aerodynamic coefficients were



obtained during wind tunnel runs. The test results have been summarized in Table 1. The other type of fiber optic strain balance is based on FBG fiber optic sensor, with the shift of FBG reflected wavelength to pick up the strain. Shenyang Aerospace University developed a five-component fiber grating balance of aerodynamic force measurements in low speed wind tunnel, and its strain sensitivity is estimated to be $0.83 \mu\epsilon$, and has the same accuracy as the conventional strain balance (better than 0.3%) [68, 69].

The main factors limiting the fiber optic strain balance performance are the installation quality of optic strain gauge and the thermal output of balance, with the thermal gradient as key factor to affect the axial force measurement. Therefore, proper thermal-insulation techniques should be taken to decrease the temperature fluctuation. However, for the wind tunnel experiment at high temperature for a long time, temperature compensation for optic fiber balance is a key issue. The conventional way to solve this problem is to use an individual temperature sensor to obtain the temperature and to compensate the temperature effect of strain gauge [70–72]. But, this way is quite unreliable and unrepeatable in the wind tunnel, as the temperature sensor insufficiently analyze the thermal variations occurring within the balance structure, especially for the hypersonic force balance designed to work in a highly fluctuating temperature environment. Therefore, it is

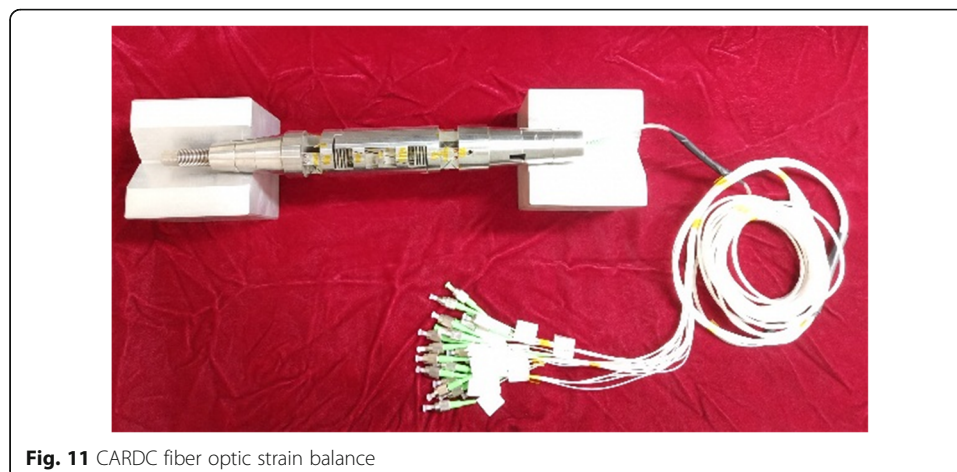


Table 1 Static calibration and wind tunnel test results of the CARDC fiber optic strain balance [67]

Component	Design Load	Calibration Accuracy	Experimental repeatability	
			Condition 1 ^a	Condition 2 ^b
F_A	360 N	0.17%	0.85%	0.83%
F_N	700 N	0.30%	0.58%	0.88%
M_z	±48 N·m	0.33%	0.88%	0.93%

^aFreestream Mach number $Ma = 3.974$, total temperature $T_0 = 287$ K, total pressure $P_0 = 0.4$ MPa

^bFreestream Mach number $Ma = 8.052$, total temperature $T_0 = 740$ K, total pressure $P_0 = 5.0$ MPa

suggested by the authors to adopt a mixed FPI structure to simultaneously measure the strain and the temperature [73–76]. Additionally, MEMS process is helpful to keep the sensor in consistent performance and compact structure, to reduce the thermal gradient arising from temperature change. However, this method has to be tested abundantly in spite of the above-mentioned advantages.

4.2 Strain sensing at high temperature

The current strain sensors mainly include the electric resistance, piezoresistive, piezoelectric and fiber optic strain gauges. Thermal experiment of hypersonic aircraft structure needs to study precise and reliable strain gauging methods under extreme conditions. Additionally, in the combustors of turbine engines (1300~1400 °C), hypersonic aircraft engines (~ 2000 °C) and rocket propellers (~ 3000 °C), strain sensors are also needed to pick up the instantaneous stress in combustors and turbine blades, learning the combustion status and the operation level. As shown in Fig. 12, commercially available piezoresistive, resistive and piezoelectric sensors are limited to work at 800 °C or less [77–79].

At the end of the twentieth century, NASA Dryden realized that fiber optic sensors have potential capability to solve the problems occurring to the strain measurement experiments of hypersonic aircraft structure, and comprehensively researched the optic fiber experiment techniques at high temperature. NASA Dryden strain test development is shown in Fig. 13 [80].

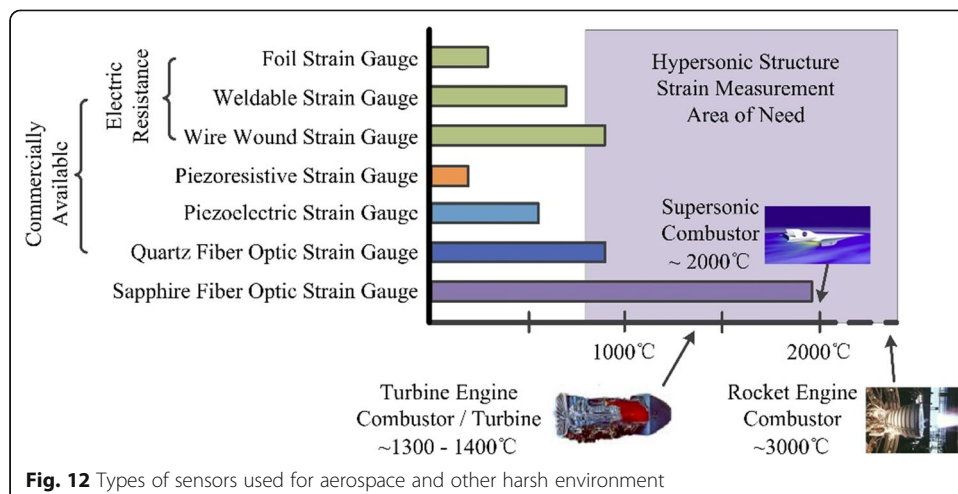


Fig. 12 Types of sensors used for aerospace and other harsh environment

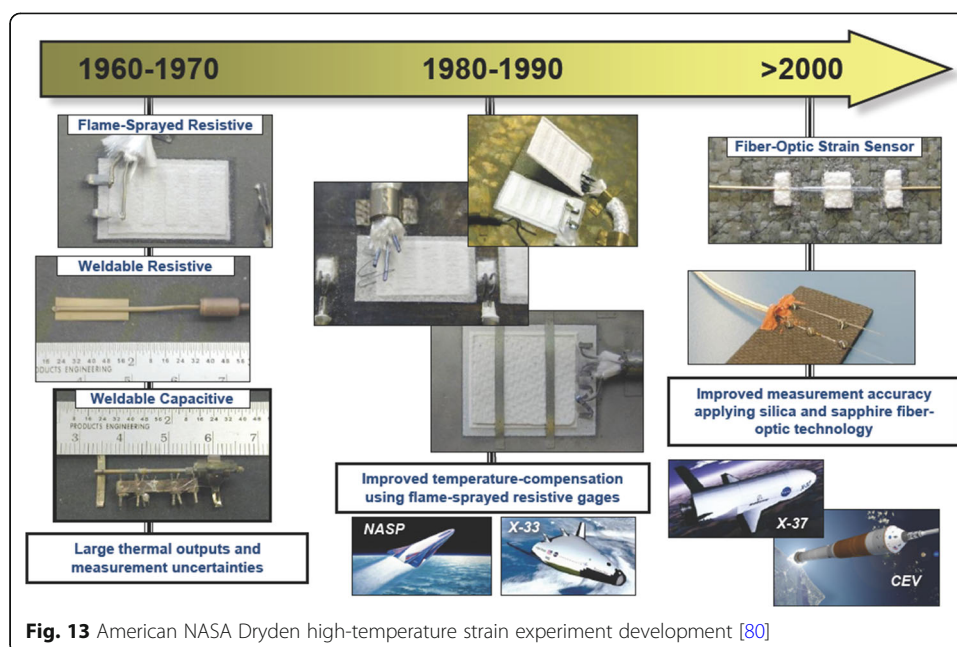


Fig. 13 American NASA Dryden high-temperature strain experiment development [80]

NASA Dryden Flight Loads Laboratory (FLL) carried out the following tests: FBG and EFPI strain sensors were mounted on Inconel, C/C and C/SiC substrate in the way of thermal spraying; verification of fiber optic sensors at conditions of high/room temperature; static thermal combined load; ground thermo-structural experiment and flight experiment; development of portable high-temperature fiber experiment system for the ground simulation experiment and the flight experiment [81]. In 2003, at the thermo-structural experiment on C/C Aileron control panel of NGLT project, there were 14 EFPI sensors mounted which picked up the temperature up to 900 °C; at the ground thermo-structural experiment on C/SiC fuselage wing in NGLT, there were 14 EFPI sensors mounted, with sensing temperature beyond 1010 °C [82]. At present, NASA Dryden and Lambda are working together to develop the sapphire fiber strain sensors, with upper limit of temperature required to be 1650 °C [83].

One difficulty of strain measurements at high temperature is mounting technique of the sensors. Although the adhesive way is easy to use, thermal spraying is still the first choice by NASA Dryden [84]. Figure 14 depicts the thermocouple and the fiber strain sensor mounted in thermal spraying way. In addition, adhesive way not only corrodes the thermocouple or the alloy in strain gauge, but also has potential adhesion failure since the adhesive resin would contract crack. Nevertheless, the thermal spraying technology is suitable for thermal structures of C/C and C/SiC being mounted with sensors. NASA Dryden has conducted the study on the technologies of sensors mounted onto the various materials, including the surface treatment suitable for base surface and the optimal plasma painting parameters (powder type, power, movement speed and spraying distance), the optical selection of the most practical adhesives and the improvement of the way to protect the fragile sensors during the severe mounting procedures.

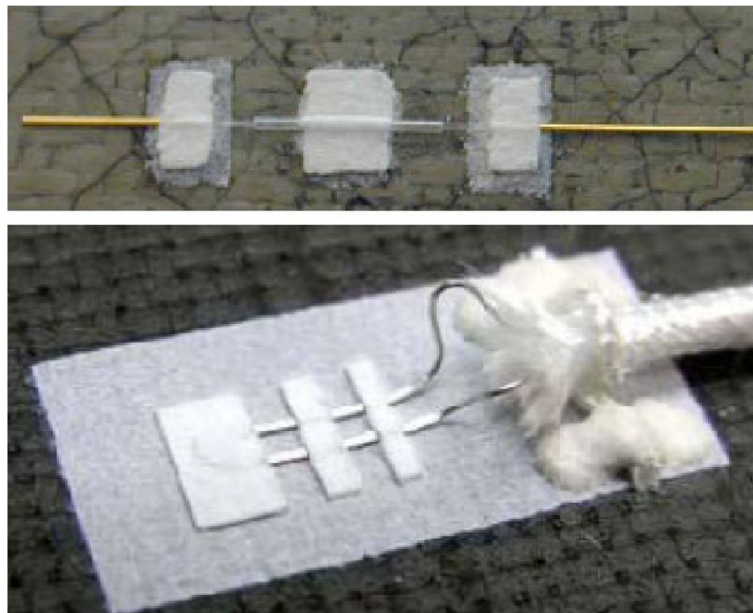


Fig. 14 Sensors mounted through thermal spraying [84]

4.3 Fiber optic high temperature sensing

As hypersonic aircrafts fly at high speed in the atmosphere for a long time, generating quite high dynamic pressure and aerothermodynamic heating effect, special heat protective measures should be taken to make sure the thermal structures of control panel of hypersonic aircrafts work properly under hot flying conditions. An essential step in the development of hypersonic aircraft is to precisely measure the surface temperature of key components under the ground wind tunnel simulated thermal conditions, and then to develop a reliable thermal protection system. Unrelated to the electronic signals and the resistance to electromagnetic interference, radiation and high temperature, the quartz and sapphire fiber sensors show their advantages in severe environment.

Figure 15 shows the heat-resisting sensing system made of sapphire fiber. With a section of sapphire fiber melted onto the tail of quartz fiber, there is a refractive index difference between them, creating the first mirror of quartz fiber sensor; the second mirror is created between the other end of sapphire fiber and the air. The refractive index and the length of sapphire fiber could vary with the outside temperature, accordingly changing the length of optical chamber in fiber optic sensor. Thus, this sensor picks up the temperature, forming a heat-resisting fiber optic temperature sensor [85].

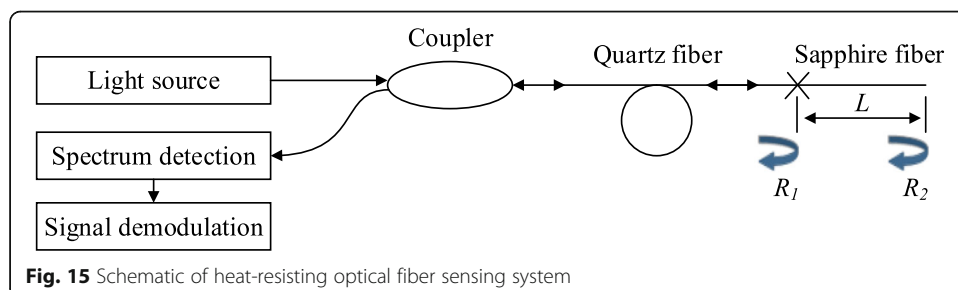


Fig. 15 Schematic of heat-resisting optical fiber sensing system

In 2010, J. Wang etc. [86] made a EFPI sensor by using two pieces of sapphire fibers to form an air gap FP chamber, enabling to measure the temperature in the range of 200~1000 °C. Besides, Y. Zhu etc. [87] made an EFPI sensor by using sapphire chip, enabling to measure the temperature in the range of 230~1600 °C. In 2015, Habisreather etc. [88] made a FBG temperature sensor based on sapphire fiber, measuring the temperature as high as 1900 °C, with resolution at ±2 °C.

The temperature sensors based on sapphire fibers have huge market prospect because of simple production and relatively high sensitivity. But, as light transmits in the sapphire fiber at different modes, the mode stability makes it difficult to improve the temperature accuracy. Furthermore, high-power femto-second laser is required to make grating through complicated process, featuring difficult maintenance and high cost. Therefore, this kind of sensors is still in research and cannot be in mass production.

4.4 Distributed stress/strain/temperature measurement

As aircraft has complicated structures and works under severe conditions, and therefore increases its possibility of failure, it is necessary to monitor the safety of structures. In comparison with the conventional sensors, the distributed fiber sensors have the advantages of light-weighted, compact, and resistance to electromagnetic interference and to corrosion at high/low-temperature, distributed matrix measurement, effective

Table 2 Research cases of distributed fiber optic sensors being applied to aircrafts [25, 89–93]

Country/Region	Applied model	Monitoring position	Achievement
USA	Predator B UAV	Wing skin structure	The real-time wing skin shapes are provided so as for aircraft to obtain the best aerodynamic performance.
	F-15 fighter	Aircraft structure	Real-time supervision of fatigue performance of aircraft fuselage
	Boeing 777	Aircraft structure	
	X-33	Liquid - hydrogen tank structure	Real-time reflection of liquid-hydrogen tank structure and the insulating layer structure.
	F-35 fighter	Main structure of wing	
EU	X-38	Aircraft structure	Able to measure the space temperature distribution and the strain of high-load structures, and estimate the residual life of main structures of aircraft.
	Some micro aircraft	Low Reynolds number in wind tunnel and physical parameters when aircraft is descending.	Able to simultaneously measure the aerodynamic load, instantaneous model position, wing deformation and distribution of flow field.
	A340 air liner	Aircraft structure	Able to record the cyclic stress load imposing onto the structure to monitor the fatigue strength of aircraft.
Japan	Some aircraft	Aircraft rubber grating	Able to integrate the damage supervision and the location based on the sensing network.
	HOPE-X space shuttle model	Aircraft structure	Able to monitor the temperature distribution of aircraft model
Spain	A380 airline	Inflected plate of composite on fuselage	This sensor is used to detect if composite of aircraft is damaged and the sticking is failed.

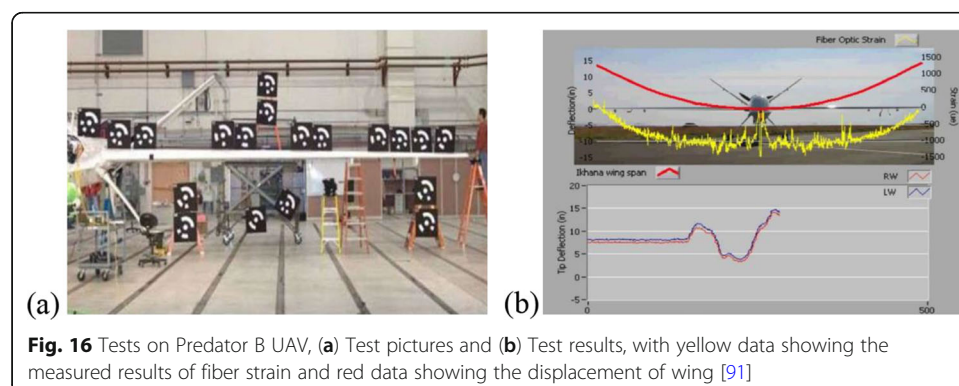
multiplexing and so on. The distributed fiber optic sensors not only measure the load, the temperature and the strain to reflect the real-time running state of machine, but also monitor the strain, the vibration and other parameters of key structures to judge the property, extent and position of damage on some component. Additionally, the distributed fiber optic sensors have the multiplexing on one fiber, significantly dropping the additional weight and wiring requirements. Studies on optical fiber sensing technologies in Europe and the USA are earlier than that in China by a few of decades, with the USA being one of the earliest countries to apply the distributed optic fiber sensors to the military aircrafts, making great contribution to this research. Table 2 lists the overseas research cases of typical distributed sensors being applied to aircrafts.

Taken the example of experiments on Predator B UAV, the deformation of aircraft wing is tested through high-density and weak-reflection FBG on the basis of OFDR. Figure 16 shows that the sensing fibers are laid on the fuselage and the wings, and 10 standard loads are imposed on the wing and the center fuselage. Then, the wing load and the displacement are respectively measured by using the laser system and the fiber sensing system. The measured results show the tip of wing has maximum displacement at 7.62 cm, with measurement error at 2.8%; after the multiple flight tests, both sides of the wing are deformed in the same way, and the measured results respectively with fiber and conventional strain gauge are basically the same with each other.

5 Summary and outlook

Because the advanced sensing technique is in big demand under environment of hypersonic wind tunnel, this article has classified and summarized the research status and the representative achievement on the fiber optic sensing technologies, giving special attention to the summary of research status at home and abroad on the popular FPI, FBG and (quasi) distributed fiber optic sensors working in hypersonic wind tunnel environment, and discussed the current problems in special optical fiber sensing technologies.

Lots of study on these optical fiber sensing technologies have been carried out, and some achievements have been achieved on the manufacturing process, high temperature sensing, multi-channel multiplexing and distributed sensors under environment of hypersonic wind tunnel. Facing the harsh and complex application environment, specified optical fiber sensing technique is still in development, with the following items to be further studied:



- (1) Sensor fabrication and packaging technologies: it is needed to design sensors with more robust structures, higher sensitivity and stronger adaptability to environment.
- (2) Multi-parameters cross sensitivity technologies: through the design of sensing elements and the processing of subsequent signals, the independent parameters, such as strain and temperature, could be accurately measured.
- (3) Sensor installation technologies: the way to protect the fragile sensors during the installation under harsh environment should be improved.
- (4) High-temperature sensing technologies: although having very optimal application prospects, the high-temperature sensors based on sapphire fibers have such problems as transmission mode, stability and reliability, hard to practically apply to engineering.
- (5) Distributed sensing space resolution and capacity: the multiplexing quantity limitation of sensing unit should be solved with the distributed sensing systems and the multiplexing methods.

In conclusion, featuring high density, high precision and multiple parameters, the large-scale optical fiber sensing system is the trend to develop the test technologies in hypersonic wind tunnel, but the current achievements are lagged far behind the complex needing to apply in hypersonic wind tunnel. Therefore, the optical fiber sensing system is still needed to be deeply and profoundly studied.

Abbreviations

I_i : Intensity of incident light; I_R : Intensity of reflected light; L : Distance between two reflecting surface; n : Fiber reflectivity; $P_c = -\frac{1}{n} \frac{dn}{dz}$: Elasto-optical coefficient of optical fiber; R : Reflectivity of the mirrors; v : Modulation coefficient of refractive index; z : Position coordinate of fiber grating in the axial direction; $\alpha_f = \frac{1}{\lambda} \frac{d\lambda}{dT}$: Coefficient of thermal expansion of optical fiber; $\xi = \frac{1}{n} \frac{dn}{dT}$: Thermal-optical coefficient of optical fiber; ε : Strain; n_{eff} : Effective refractive index of optical fiber; λ : Wavelength of incident light; λ_B : Bragg wavelength; $\lambda_{initial}$: Original wavelength of incident light; Λ : Period of uniform grating; ΔL : Change in cavity length; $\Delta n(z)$: Change of refractive index of fiber core; ΔT : Change in temperature; $\Delta \lambda_B$: Wavelength change of Bragg wavelength; $\Delta \lambda_i = 2L\varepsilon$: Wavelength change of incident light due to strain; $\Delta \lambda_T = n \frac{\Delta T}{\lambda} \frac{dn}{dT}$: Wavelength change of incident light due to temperature; $\bar{\delta n}$: Average growth value of refractive index of fiber core

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Authors' contributions

HQ reviewed the literature, and was a major contributor in writing the manuscript. FM carried out experiments regarding the fiber optic balance. YY reviewed and revised the manuscript. All authors read and approved the final manuscript.

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