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Review of femtosecond laser fabricated optical fiber high temperature sensors [Invited]

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The femtosecond laser has been an efficient tool for optical fiber high temperature sensor construction. Here, we review the progress of optical fiber high temperature sensors based on femtosecond laser fabricated fiber gratings and various types of fiber in-line interferometers in silica fibers and sapphire fibers.

Keywords: optical fiber sensors; femtosecond laser micromachining; high temperature measurement.

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1. Introduction

Optical fiber sensors have been developed rapidly in the last few decades, and more and more applications are emerging. The main advantages of optical fiber sensors include high sensitivity, light weight, small volume, anti-corrosion, immunity to electromagnetic interference, distributed and remote sensing capability, and the suitability for extreme environment monitoring such as high temperature. High temperature sensing has important applications in energy, iron-steel, aero-engine, defense, and military industries, which has induced intensive research interests in recent years[1–5].

Optical fiber high temperature sensors can be realized by different types of optical fiber structures and configurations and constructed in different types of optical fibers. The most popular fiber structures used for high temperature sensing are fiber Bragg grating (FBG)[6–14], long-period fiber grating (LPFG)[15–17], and fiber interferometers[18–33].

FBG-based optical fiber sensors are simple, compact, highly flexible, and convenient in use, and can be easily multiplexed in a series along a single optical fiber, thus achieving simultaneous multi-point sensing in a flexible manner. However, they usually have limited sensitivity (0.01 nm/°C). The FBG is essentially a simple wavelength mirror or filter, usually fabricated by exposing the optical fiber to ultraviolet (UV) laser light using the interferometric method or the phase mask technique, which causes a periodic modulation of the refractive index of the optical fiber, arising from the fiber's inherent photosensitivity[34,35]. The FBGs fabricated by use of a UV laser exhibit poor stability in the high temperature environment, and the grating structure "washes out" at temperatures close to 700°C[36]. Such a problem can be overcome by use of femtosecond laser fabricated gratings, as will be described later.

LPFG-based sensors exhibit higher sensitivity to external perturbations than that of FBGs. LPFGs exhibit periodic structures that couple light from the guided core mode to the cladding mode at resonant wavelengths satisfying the phase matching condition. The transmission spectra of LPFGs consist of a series of attenuation bands centered at the resonant wavelengths, which are sensitive to grating period, grating length, and environmental parameters such as strain, bend, and temperature. LPFG-based sensors have a relatively large device size (on the order of centimeters) and a wide 3 dB bandwidth, which leads to a low measurement resolution. Moreover, the LPFG is sensitive to an external refractive index and bending, thus producing cross sensitivity.

Optical fiber interferometric high temperature sensors are featured with high sensitivity, without age decaying or structure erasing problems faced by FBGs. Different types of interferometer configurations have been developed for high temperature sensors, such as the Mach–Zehnder interferometer (MZI)[18–21], the Fabry–Perot interferometer (FPI)[22–25], and the Michelson interferometer (MI)[26-28]. Especially, the fiber in-line interferometer is a miniature and versatile optical fiber sensing device that can operate conveniently and in a flexible manner.

Besides the frequently used conventional single-mode fiber (SMF), multimode fiber (MMF), photonics crystal fiber (PCF) or microstructured fiber, microfiber, and other specialty optical fibers are also employed for high temperature measurement[29–33]. As the glass transition temperature of silica is around 1050°C[37], for higher temperature sensing, the sapphire fiber has to be used[37–45].

In the past two decades, the femtosecond laser has become a powerful and flexible tool for optical fiber high temperature sensor fabrication. It can be used for a variety of materials, with ultrashort processing time, high processing precision, and small heat affected zone[46–49]. The femtosecond laser inscribed gratings can effectively avoid the age decaying or structure erasing problem and exhibit high temperature sustainability. The femtosecond laser can flexibly fabricate different types of optical fiber in-line interferometers, which highly improves the device compactness and operation convenience. Especially, the femtosecond laser provides an efficient means for processing sapphire fibers and allows FBGs be inscribed in sapphire fibers, which effectively supports high temperature sensing beyond 1200°C.

In this paper, we will review the recent progress of femtosecond laser fabricated optical fiber high temperature sensors. The main interests lie in the sensor device based on femtosecond laser fabricated fiber gratings and various types of fiber in-line interferometers in silica fibers and sapphire fibers.

2. Femtosecond Laser Fabricated Fiber Gratings for High Temperature Sensing

FBGs are usually written by use of either the phase mask method or point-by-point technique[6,7,10,11,50,51]. The point-by-point technique is more flexible for FBG resonant wavelength selection; however, by using the phase mask method, rapid and massive production can be realized, and the grating quality is relatively easy to be guaranteed.

The UV laser is typically used to write FBGs, in which the refractive index modulation produced depends on the photosensitivity of the fiber materials and usually has poor sustainability at high temperatures. The femtosecond laser can produce the refractive index modulation in almost any kind of transparent material[52], and the type II FBGs (damage FBGs) produced have excellent high temperature stability up to the glass transition temperature, which is likely due to the nonlinear self-focusing process, where ultrahigh pulse power may affect the glass structure[53].

Figure 1 demonstrates the structures of type I and type II FBGs written by the femtosecond laser. Type II FBGs have a structure with a permanent refractive index change, are much more stable under high temperatures than type I FBGs, which refers to the grating formed under normal laser irradiation intensity, and can be erased at a relatively low temperature.

One of the limitation factors for further enhancing the thermal stability of the FBG is the residual stress that exists in the optical fiber fabrication process, caused by the mechanical property and thermal expansion coefficient differences between the fiber core and cladding[54]. Such a residual stress can be relaxed through using a high temperature annealing treatment.

Figure 2 shows a long-term thermal stability test on type II gratings. It can be observed that the FBGs written in the fibers with pre-annealing treatment of 1100°C have enhanced thermal stability, almost unaffected by the thermal exposure to temperatures up to 1200°C.

One of the problems of the pre-annealing treatment of fiber is that the fiber becomes brittle, which creates difficulty in the grating fabrication. Such a problem can be alleviated to some extent by introducing compressive residual stress in FBGs through high temperature annealing followed by a rapid air quenching treatment, which can build up compressive residual stresses in the optical fiber, similar to the annealing of the glass[14].

Figures 3(a) and 3(b) demonstrate the evolution of the grating reflectivity and the resonance wavelength, respectively. It can be observed that the pre-stressed gratings exhibit clearly enhanced thermal stability, which is almost unaffected by thermal exposure at temperatures up to 1200°C, and there is only a slight fluctuation of the grating strength during the 26 h test.

In a recent investigation, both doped silica fiber and pure silica fiber were tested at high temperature[55]. It is found that the pure silica fiber can maintain stability at the temperature higher than that of the doped silica fiber.

FBGs are also written by femtosecond lasers in the MMF[56,57] and PCF[58] suspended-core microstructured optical fiber[33] for multiple parameter measurement at high temperature. By moving the fiber with a tilt angle, tilted FBGs can be fabricated by the femtosecond laser and used for high temperature sensing[59].

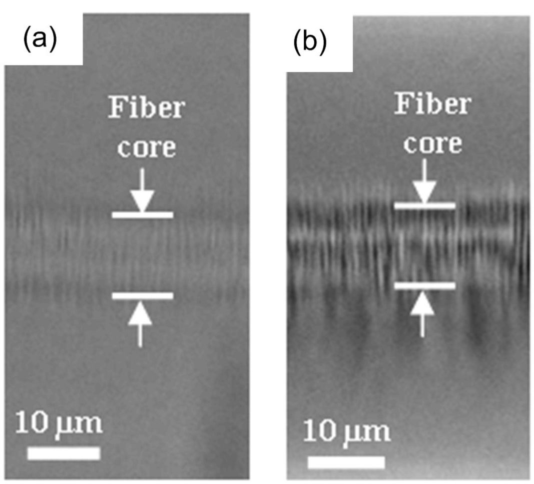

Fig. 1. Optical microscope images of FBGs inscribed by IR fs lasers[13]. (a) Type I grating; (b) type II grating.

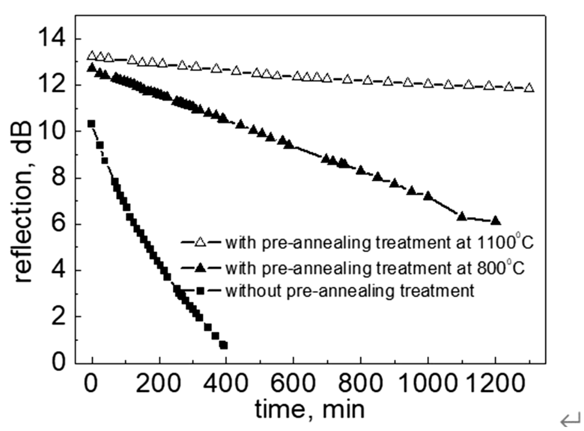

Fig. 2. Change in the reflectivity of the type II-IR FBGs inscribed in normal and pre-annealed fibers over a 1300 min period at an annealing temperature of 1200°C[12].

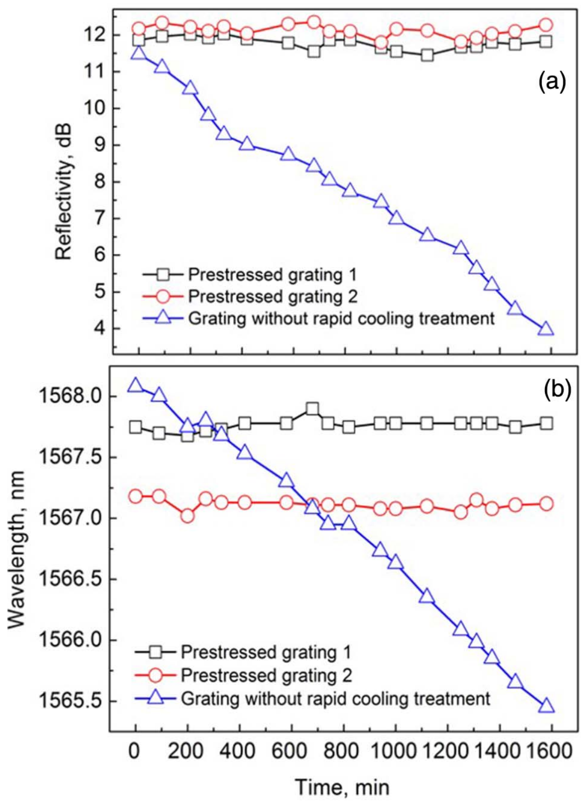

Fig. 3. Evolutions of (a) the reflection and (b) the resonant wavelength of the pre-stressed FBGs (fabricated using 550 μJ pulse energy) over 26 h at the annealing temperature of 1200°C.

In Ref. [60], parallel structured multiple FBGs within the core of the SMF are fabricated by use of the femtosecond laser and point-to-point technique. The whole grating length is 500 μm and it can be used to realize high temperature sensing up to 1100°C, with a high spatial resolution of the sub-millimeter scale, which is much better than that of the FBG written by the UV laser (larger than 1 cm).

Recently, a linear-cavity fiber laser based on an FBG fabricated by a femtosecond laser has been developed and tested for its high temperature characteristics, such a fiber laser can operate stably at 1000°C with a temperature sensitivity of 15.9 pm/°C in the range of 300–1000°C[61].

The femtosecond laser inscribed LPFGs are reported in Refs. [62,63] with a relatively large temperature sensitivity of more than 100 pm/°C.

3. Optical Fiber In-Line Interferometers for High Temperature Sensing

Although many optical fiber interferometers can perform high temperature sensing, fiber in-line interferometers have the advantages of compact size, flexible arrangement, and convenient operation. By use of an efficient femtosecond laser micromachining technique, various types of fiber in-line interferometers have been developed and used for high temperature sensing.

Figure 4 shows the schematic examples of the femtosecond laser fabricated FPI, MZI, and MI suitable for high temperature monitoring. In Fig. 4(a), part of the fiber cladding and a small section of the whole fiber core are removed by femtosecond laser micromachining, and an open air-cavity is created. Part of the incident light traveling in the fiber core is reflected by the first end face of the air cavity, and the rest keeps traveling in the air cavity and is reflected by the second end face of the air cavity before returning to the fiber core at the first end face position, thus forming an FPI.

Figure 4(b) is similar to Fig. 4(a), but only a small section of half of the fiber core is removed, which allows that part of the incident light to pass through the open air cavity, while the rest remains traveling in the fiber core; both are recombined at the air-cavity end and form an MZI.

In Fig. 4(c), a section of the optical fiber, including half of the fiber core and cladding, is removed. The incident light traveling in the fiber core is firstly divided into two beams and reflected by the two fiber end faces, respectively, before recombining in the fiber core at the first fiber end face position and forming an MI.

The fiber in-line interferometers can be constructed by using different fibers, fiber structures, and configurations.

Similar to the configuration shown in Fig. 4(a), a fiber in-line FPI can be constructed by drilling a micro-channel crossing the fiber core using femtosecond laser [64–66]. Such an FPI can sustain the high temperature up to 1100°C. When the microchannel is near the end of the SMF, a three wave FPI can be formed and used for high temperature sensing up to 1000°C[67]. An FPI is constructed by use of a femtosecond laser inscribed refractive index modified dot in the fiber core near the end of the SMF, which has the temperature sensitivity of 13.9 pm/°C and 18.6 pm/°C in the range of 100°C–500°C and 500°C–1000°C, respectively[68]. By fusion splicing an SMF and a no-core fiber (NCF) to create an inner air cavity, followed by using a

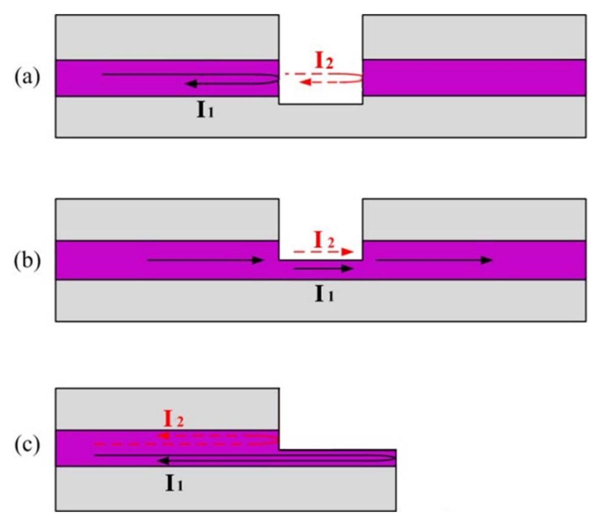

Fig. 4. Schematics of the femtosecond laser fabricated fiber in-line interferometers. (a) FPI, (b) MZI, and (c) MI.

femtosecond laser for precision fiber cleaving to form a thin diagram, a miniature FPI sensor is produced for high temperature and high pressure sensing[69].

Recently, in-fiber reflection mirrors have been inscribed in SMFs, NCFs, and MMFs by a femtosecond laser, which can be flexibly arranged to form cascaded FPIs in a series or a parallel structure with precisely controlled FP cavity length[70–74], with high temperature sustainability up to 1100°C. Moreover, fiber gratings and FPIs can be combined by inscribing nanogratings in the fiber core and be used as in-fiber reflection mirrors to create an intrinsic FPIs for high temperature sensing up to 1000°C[75].

As shown in Fig. 4(b), by removing part of the fiber core and cladding using femtosecond laser micromachining, an MZI is formed and used for high temperature monitoring up to 1100°C[19]. The system is compact, reliable, and can detect the temperature at precise locations. By combing femtosecond laser micromachining together with fusing splicing techniques, microholes or microchannels are created, which can form MZIs and be used for high temperature sensing[20,21,76]. The MZI high temperature sensor can also be fabricated in microfibers[77].

In Ref. [78], a fiber in-line MI similar to that displayed in Fig. 4(c) is constructed, with the help of femtosecond laser micromachining. The device can be used for high temperature sensing up to 1000°C, with the temperature sensitivity of 14.72 pm/°C. In Ref. [28], an inclined narrow slit inside the SMF crossing the fiber core is created by using femtosecond laser micromachining, and the narrow slit plays the role of an in-fiber beam splitter. The optical fiber in-line MI fabricated is found to have good high temperature sustainability up to 1000°C. In Ref. [79], a fiber in-line MI high temperature sensor is constructed by using a femtosecond laser to cut a 45° fiber end.

4. Femtosecond Laser Fabricated FBGs in Sapphire Fibers for High Temperature Sensing

Since the glass transition temperature of the silica is around 1050°C, the long-term stability of the SMF and microstructure fiber is typically below 1200°C. For the high temperature optical fiber sensing of greater than 1200°C, the sapphire fiber has to be utilized[37,39,41,44,45,80–82], and the material has a melting temperature of around 2050°C[37]. By femtosecond laser pulse irradiation, FBGs can be effectively inscribed in sapphire fibers and used for high temperature monitoring up to 1900°C[82]. As the sapphire fiber is highly stable, it can operate in air and in inert gases at an extremely high temperature environment. However, the problems of FBGs in sapphire fibers are broad bandwidth and poor spectral quality because of the associated multimode nature. The efforts made to overcome such difficulties are the use of the line-by-line scanning technique[44] and inscribing the FBG on a micro-single-crystal sapphire fiber[80]. A proposal is to inscribe FBGs along the waveguide written in the sapphire fiber, and the reflection peak of the Bragg grating obtained is expected to have reduced bandwidth and hence improved measurement resolution, as achieved in NCFs[71].

5. Conclusion

Various types of optical fiber sensors based on FBGs, LPFGs, and fiber in-line interferometers have been fabricated in SMFs, MMFs, and microstructured fibers by use of a femtosecond laser for the high temperature sensing up to 1200°C and, for a long time, limited by the glass transition temperature of silica. For the higher temperature sensing up to 2000°C, the femtosecond laser is even an indispensible tool for writing FBGs in sapphire fibers.

Compared with other techniques for optical fiber high temperature sensor construction, femtosecond laser irradiation is featured with wide material processing suitability, rapid processing speed, high processing precision, and small heat affected zone, which ensures good processing quality and flexible fabrication capability. It is expected that the femtosecond laser will play a more and more important role in fabricating optical fiber high temperature sensors suitable for extreme environment monitoring.

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