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Review

Review of Femtosecond Laser Fabricated Fiber Bragg Gratings for High Temperature Sensing

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Abstract: This paper reviews high temperature sensing applications based on fiber Bragg gratings fabricated by use of femtosecond laser. Type II fiber Bragg gratings fabricated in the silica fiber can sustain up to 1200 ℃ while that fabricated in the sapphire fiber have the good thermal stability up to 1745 ℃.

Keywords: Fiber Bragg grating, femtosecond laser, high temperature sensing, silica fiber, sapphire fiber, microstructured fiber

1. Introduction

The fiber Bragg grating（FBG）is one of the most popular optical components widely used in optical networks, wavelength-division-multiplexed optical communication systems and optical fiber sensors due to its small size, ease of fabrication, compatibility with other fiber components and low cost. Many FBG based sensor arrays have been used in civil structures, aircrafts, warships, oil pipelines, oil and gas well reservoirs, and nuclear reactors for *in situ* structural health monitoring. However, conventional FBGs are usually fabricated by using ultraviolet (UV) laser irradiation which requires the photosensitivity of the fiber core material, and their thermal stability is poor and hence may not be suitable for high temperature sensing in harsh environments.

Recently, the femtosecond (fs) laser technology is exploited to write FBGs in optical fibers without the requirement of the material photosensitivity, and the gratings fabricated have outstanding thermal stability. Thus, the fs-laser inscribed FBG becomes a promising candidate for high temperature sensing applications. During the fs-laser interaction with the glass fiber, the energy absorption takes place through nonlinear phenomena such as multiphoton, tunnelling and avalanche ionization. As long as the absorbed energy is high enough, the catastrophic material damage occurs, which leads to the formation of voidlike structures [1]. Such intensive index modulation of the fiber material ($\sim 10^{-3}$) in fs-laser inscribed FBGs has the outstanding thermal stability compared with that of UV laser induced gratings.

In this paper, the authors firstly reviews the FBGs inscribed by the fs-laser on silica fibers for high temperature sensing. Some effective methods to enhance the grating performance are included. Secondly, fs-laser inscribed FBGs on several specialty fibers i.e. the sapphire fiber and the microstructured fiber are reviewed. Unusual material properties and structural characteristics of these fibers make the FBGs fabricated be more

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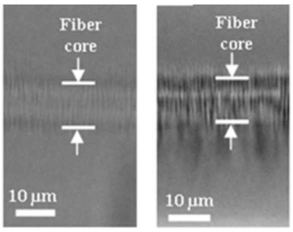
suitable for the applications in hash environments.

2. Fs-laser induced FBGs in silica fibers

The first FBG was inscribed on the standard Ge-doped telecom fiber (corning SMF-28) by use of 800 nm, 120 fs laser irradiation and a deep-etch silica zero-order nulled phase mask in the Mihailov's group in 2003, and the gratings were stable and did not erase after two weeks at 300 ℃ [2]. Later, both infrared radiation (IR) and UV fs-laser sources were used to fabricate high-quality retroreflecting FBGs by the phase-mask method [3–6]. In 2004, the direct point-by-point inscription of FBGs by the fs-laser was reported by the Bennion's group, and this method did not require the phase mask and offered the remarkable technological flexibility. The FBGs obtained were stable at the temperature of up to 900 ℃ [7]. Being different in the thermal stability and material index modulation, fs-laser induced FBGs can be divided into type I and type II, which exhibit different intensity thresholds, annealing behaviors and grating structures [8].



(a) (b)

Fig. 1 Optical microscope images of FBGs inscribed by the IR fs laser [12]: (a) type I-IR 125-fs grating and (b) type II-IR 125-fs grating.

Figure 1 compares the grating structure of type I-IR FBGs with that of type II-IR FBGs (where the IR suffix denotes the use of an IR laser in the grating inscription). Type II-IR FBGs have an index change larger than 10^{-3} and are stable at the temperature in excess of 1000 ℃ [8–11], but type I-IR FBGs show the poor thermal stability that is similar to standard UV gratings. Type II-IR FBGs were achieved in H_2-free and H_2-loaded SMFs and these gratings could both sustain high temperature of up to 1000 ℃. The experimental results of annealing at 1000 ℃ over 12 hours are shown in Fig. 2.

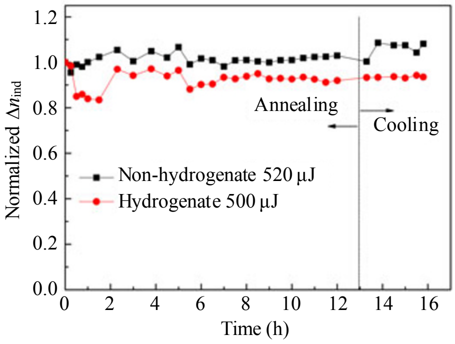


Fig. 2 Reflectivity of type II-IR FBGs inscribed in H_2-free and H_2-loaded SMFs over 12 hours at 1000 ℃ annealing followed by 4 h cooling [10].

However, the use of fs-laser inscribed FBGs in SMFs for ultrahigh temperature monitoring applications is still a challenge because of the irreversible decay of the grating reflectivity at the temperature of higher than 1050 ℃. It is known that the glass transition temperature (T_g) of the pure SiO_2 is about 1330 ℃, and the material doping in the silica fiber would reduce the T_g to a certain degree. The highest temperature at which silica fiber can survive is lower than 1330 ℃. Li *et al.* believed the residual stress existed in the fiber had some negative effects on the fiber reliability, grating quality and consequently the thermal stability. In their experiments, type II-IR FBGs were inscribed in SMFs with the relaxed residual stress by use of an annealing treatment at the high temperature. Figure 3 compares the long-term thermal stability of the FBGs which undergo different pre-annealing treatments. The FBG with the pre-annealing treatment at 1100 ℃ demonstrates the excellent thermal stability at the temperature of up to 1200 ℃ for more than 20 hours [12].

However, the fiber became significantly brittle after a few hours annealing treatment at the high temperature, which created a difficulty in the grating fabrication, and the FBG-based sensor head was not robust, which essentially limited its application. Later, the same authors proposed the post-fabrication treatment of the FBG for the high temperature enhancement [13]. The compressive residual stress was deliberately introduced in the fs-laser inscribed FBGs through the high-temperature annealing and the rapid air quenching treatment. The prestressed FBGs were thermally stable at the temperature of up to 1200 ℃ and exhibit higher robustness than that reported in [12].

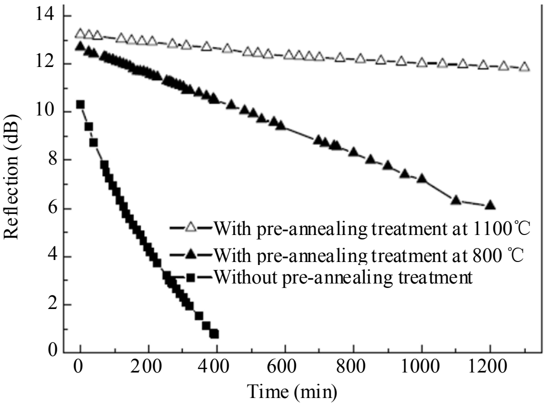


Fig. 3 Reflectivity of type II-IR FBGs inscribed in normal and pre-annealed fibers over a 1300-minute period at 1200 ℃ [12].

Grobnic *et al.* used the IR fs-laser to fabricate FBGs in a highly radiation-hard F-doped fiber, on which it was very difficult to write the grating with the UV laser. The grating sensors were highly resistant to the gamma radiation, which made them be suitable for the high temperature measurement in nuclear reactors [14]. An effective way to improve the thermal stability of the fiber sensor was to make a package such as a gold coating of the fiber. Type II-IR FBGs were fabricated in a silica-based 400-μm clad single mode fiber (PLMA-GDF-10/400 from Nufern) [15]. The grating was "self-packaged" by the large-diameter cladding and maintained the good mechanical integrity after more than 100 h annealing at 1000 ℃.

Table 1 summarizes the above mentioned FBGs fabricated by the fs-laser in various silica fibers and compares their thermal performances.

Table 1 List of fs-laser induced FBGs in silica fibers.

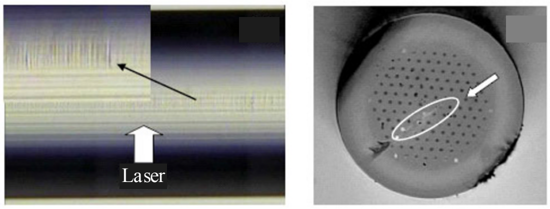
Fiber	Grating types	Treatment	Characteristics
SMF[2, 6]	Type I	None	Stable to ~300 ℃
SMF[8–11]	Type II	None	Stable to ~1000 ℃
400-μm-clad SMF[15]	Type II	None	Stable to ~1000 ℃
F-doped fiber[14]	Type I	H_2 loading or not	Resistant to the gamma radiation in the high temperature
SMF[12]	Type II	Residual stress relaxing by the pre-annealing of the SMF	Stable to ~1200 ℃, easily brittle
SMF[13]	Type II	Prestressed grating by the high temperature annealing and the rapid quenching treatment	Stable to ~1200 ℃

3. Fs-laser induced FBGs in specialty fibers

Recently, FBGs have been successfully inscribed in several specialty optical fibers which might be great candidates for high temperature sensing. It is known that the single crystal sapphire has a very high melting temperature (~ 2050 ℃). Being different from the silica-based SMF, sapphire fibers are made in the form of rods without the cladding layer which allows them to be operated in multimode at telecommunication wavelengths and sensitive to the bending loss.

D. Grobnic *et al.* reported, for the first time, the fabrication of a retroreflective FBG in the multimode sapphire fiber. The FBG was tested to be thermally stable up to 1500 ℃ [16]. In 2009, Busch *et al.* used the IR fs-laser to produce sapphire FBGs by a multimode excitation approach, and the sapphire FBGs produced showed no degradation in the reflection strength at the high temperature of up to 1745 ℃ [17]. However, at very high temperature, the signal-to-noise ratio (SNR) of the reflected FBG signal would decrease by the strong background spectrum produced by the thermal blackbody radiation. The high SNR could be obtained by the excitation of the fundamental/low-order modes of the sapphire FBG. A dual-parameter (stress and temperature) sensor was realized based on the sapphire FBG [18]. By monitoring the signal level of the thermal blackbody radiation as a temperature reference, the wavelength shift dependent on temperature was decoupled from the strain. This device might be useful for monitoring strains in high temperature environments.

The photonic crystal fiber (PCF), which is one of the most important microstructured fibers, provides much convenience to improve the thermal performance of high-temperature sensors. In 2005, the fs-laser at 267 nm was firstly employed by Fu *et al.* to fabricate FBGs in the hydrogen-loaded pure-silica PCF [19]. The hydrogen loading enhanced the photosensitivity, possibly by creating the defect-based photosensitivity pathway in the bulk silica, but the poor thermal annealing investigation indicated that such a grating was not type II. With the same method, FBGs were fabricated into the core of the all-solid PCF with Ge-doped cladding rods, and the grating structure is shown in Fig. 4. The grating worked in the single-mode reflection and was thermally stable up to 700 ℃, which was better than that of the type I fs-laser-induced grating in the SMF [20].



(a) (b)

Fig. 4 Optical microscope images of the FBG inscribed in the all-solid PCF in the (a) longitudinal and (b) the cross section of the fiber [20].

Pressure sensors operated at the high temperature have many important applications in the energy industry such as the operation of gas turbines, coal boilers, nuclear power plants and others. A novel FBG pressure sensor based on the fs-laser fabricated FBG in air-hole micro-structured fibers was developed for the high-temperature operation above 800 ℃ [21]. In comparison with other fiber optical pressure sensors, such FBG pressure sensors can be easily multiplexed for a sensor network.

Table 2 summarizes the mentioned FBGs fabricated by the fs-laser in the specialty fibers for high temperature applications.

Table 2 List of fs-laser induced FBGs in specialty fibers.

Fiber	Grating type	Treatment	Characteristics
Sapphire fiber[17]	Type II	None	Stable to ~1745 ℃
Pure-silica PCF[19]	Type I	H_2 loading	Stable to ~300 ℃
All-solid PCF[20]	Type II	None	Stable to ~700 ℃
Air-hole PCF[21]	Type II	None	Stable to ~800 ℃

4. Conclusions

High temperature sensing applications using the FBGs inscribed by the fs-laser have been reviewed. Compared with the traditional UV-laser method, the photosensitivity of the fiber material and the hydrogen loading treatment are not required in the fs-laser approach. Owing to the ultrahigh peak power of the fs-laser, the FBGs can be inscribed in the fiber made of any material. By controlling the incident laser power, type I and type II gratings can be formed which exhibit different thermal stability. The thermal performance of type II FBGs can be further enhanced through many methods such as pre-annealing to relax the residual stress, to introduce the prestress and self-packaged, etc. The sapphire FBGs could conceivably be used at the temperatures of up to 2000 ℃. Besides, the FBGs achieved in PCFs also demonstrate certain superiority in the field of high temperature sensing.

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