

Research paper

Sapphire fiber Bragg gratings for high temperature and dynamic temperature diagnostics



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HIGHLIGHTS

- Temperature sensing using Sapphire fiber Bragg gratings up to 1900 °C is shown.
- For temperatures >1500 °C a temperature resolution of ± 1 K was achieved.
- High speed temperature monitoring at a rate of 20 Hz was demonstrated.
- The temperature distribution in an inductive furnace at 1500 °C was determined.

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ABSTRACT

This paper reports on a new kind of temperature sensor operating over an extremely large temperature range at high monitoring speeds. The sensor utilizes fiber Bragg gratings inscribed into multimode single crystalline Sapphire fibers, basically providing temperature control via an optical reflection signal. The gratings operate up to 1900 °C, which is the highest temperature determined using Bragg grating so far, and allow signal processing with a temperature resolution better than ± 2 K. The sensor uniquely provides fast dynamic temperature monitoring at an unprecedented rate of 20 Hz. Overall, fiber Bragg grating inside Sapphire fibers provide a new base for precise high-temperature measurement with key advantages such as signal multiplexing, large temperature bandwidth and insensitivity to electromagnetic fields.

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1. Introduction

High temperature processes are of great significance in production and optimization of many industrially-relevant materials. For instance melting of metals or glass, crystal growth or the fabrication of ceramics require processes at temperatures higher than 1000 °C. Moreover, optimization of high-temperature processes in heat engines or in reactor cores is the key to a more efficient and safe energy supply.

For all those processes, a precise temperature control is essential, and various sensor concepts for measuring such high temperatures are available. The optimization of high temperature sensors is an ongoing research activity, as presented in Ref. [1]. Noble metal

thermocouples can be used in air up to 1700 °C. However, diffusion processes can lead to changes in the thermal voltages and therefore to signal drift, which ultimately limits the practical lifetime of the device as it is being reported in Ref. [2]. Thermocouples therefore require regular checks or might even need to be replaced. (Refs. [3,4] being published in a distance of 40 years show that minimizing such aging effects is an ongoing research activity.) Furthermore, a metal based sensor like a thermocouple is not applicable in an electro-magnetically polluted environment.

Pyrometers, those described in Ref. [5], can operate in different atmospheres at temperatures >2000 °C. These devices respond fast and allow studying dynamic processes as shown in Ref. [6]. Moreover, pyrometers are also used to investigate moving objects as demonstrated in Ref. [7]. However, pyrometers require direct optical access to the hot surface, which prevents them from being used in many important applications. For instance the temperature distribution inside a sealed furnace cannot be determined. In

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general, modifications of the hot surface can lead to changes in the emissivity and thus to errors in the measurements. Two color pyrometers are one solution to overcome this problem as discussed in Refs. [8,9].

Using fiber optic based sensors is an alternative approach. Such sensors can be applied in various atmospheres and are not influenced by electromagnetic fields. In Ref. [10] various optical methods to measure and determine temperatures in gas turbines are discussed. Conventional optical fiber sensors are based on fused silica, which reveals a limit in the maximum reasonable temperature of 1200 °C, which is close to the glass transition temperature of fused silica. Measuring higher temperatures therefore requires alternative materials. One promising candidate is single crystalline Sapphire in fiber form. Sapphire has a wide transparency from the ultraviolet (UV) to the far infrared domain (The optical parameters for Sapphire fibers were published in Ref. [11]). Single crystalline fibers are grown from the melt and can be used up to their melting point of about 2050 °C. The authors of Ref. [12] tested extrinsic Fabry–Perot interferometers for temperature measurements up to 1600 °C. A promising alternative approach is the inscription of Bragg gratings in the single crystalline Sapphire fiber (SFBG) using femtosecond laser sources (This technique was first described in Ref. [13]). This kind of inscription relies on non-linear multi-photon absorptions effects since Sapphire does not show any photosensitivity up to moderate pulse intensities with a mean power <500 mW. On the other hand a mean power >650 mW leads to fiber destruction. Using the phase-mask technology at a wavelength of 800 nm, second order gratings were successfully inscribed and tested up to temperatures of 1740 °C as it is reported in Ref. [14]. A new development is the inscription of first order gratings and grating arrays using a Talbot interferometer and an inscription wavelength of 400 nm [15].

In this paper the temperature dependence of SFBGs and their application as temperature sensors at very high temperatures between 1200 °C and 1900 °C as well as for fast responding sensors will be presented. The measurement of the temperature distribution in an inductively heated tube furnace will reveal the specific advantage of SFBG in comparison to thermocouples and pyrometers.

2. Fiber Bragg gratings

In Ref. [16] the general properties of Fiber Bragg gratings (FBG) are presented. FBGs are a periodic perturbation of the refractive index of the core over a length of about a few millimeters. The perturbation leads to the reflection of light a certain wavelength, for which the Bragg condition is satisfied [16]:

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

Here, Λ is the grating period, λ is the vacuum wavelength, and n_{eff} is the effective refractive index of fundamental core mode of the fiber. A weak refractive index modulation of $\Delta n \approx 3 \cdot 10^{-5}$ is enough to generate a reflectivity of several percent, being sufficient for signal processing in many sensor applications. The spectral bandwidth of the reflection peak of a single mode fiber grating is typically well below 1 nm. A very efficient production inscribing the gratings directly during the fiber drawing process is reported in Ref. [17].

Main application areas of Bragg gratings are temperature and strain sensing. Applied strain (ϵ) and changes in temperature (ΔT) lead to a shift of the Bragg wavelength $\Delta\lambda_B$ [16]:

$$\Delta\lambda_B/\lambda_B = (1 - p_\epsilon)\epsilon + (\alpha_{th} + \alpha_n)\Delta T \quad (2)$$

with p being the strain optic coefficient, α_{th} being the thermal expansion coefficient of the optical fiber and α_n being the thermo-optic coefficient. For standard single mode fibers the temperature-induced shift of the Bragg wavelength is about 10 pm/K. It is dominated by the thermo-optic coefficient. A value $\alpha_n = 9.7 \cdot 10^{-6}/K$ at 850 nm is specified for high quality fused silica material in Ref. [18]. In comparison the thermal expansion of fused silica is small: $\alpha_{th} = 0.57 \cdot 10^{-6}/K$.

3. Experimental

Commercial air-clad single-crystal Sapphire fibers (Micro-material Inc. diameter: 100 μm ; length <1 m, crystallographic c-axis parallel to the fiber axis) were used. The high refractive index step (0.745 for the Sapphire/air interface) and the large core diameter lead to highly multimode waveguiding (no. of modes: >200,000). The optical spectra therefore differ from conventional single mode fiber Bragg grating spectra and a new adapted signal processing was developed to identify the Bragg wavelength in SFBG. One approach is to probe multimode SFBG using a tapered single mode fiber with adapted taper diameters to produce single and low order mode reflection/transmission responses as it is described in Ref. [19], where the further signal processing is similar to conventional FBG systems. But, however, the authors of [20] report on very low signal intensities.

In this approach the entire reflected spectrum for the further signal processing was used. Due to the multimode characteristics of Sapphire fibers, all further used fiber optic components and systems are based on standard 50 μm GI silica fibers (Fig. 1). Sapphire fibers and silica fibers were connected via conventional FC/APC plugs. A superluminescent diode (SLD) with the maximum output intensity at 1545 nm wavelength and a FBG interrogator (Ibsen Photonics) were connected to a Y shape fiber coupler. An additional 50 m launch cable acts as mode scrambler, which enables excitation of all guided modes in the Sapphire fiber. The homogeneous excitation of the modes in the sapphire fiber leads to a stabilized and smoothed FBG reflection spectrum. In experiments leading to previous studies (Refs. [14,15]) it was observed, that the spectrum is also stable against moderate bending and vibrations of the fiber.

For the inscription of first order FBGs in the Sapphire fibers a frequency-doubled 800 nm femtosecond laser system (pulse duration: 300 fs, average power: 1 W, repetition rate: 1 kHz) was used. For inscription 550 mW of average power was chosen. An external dynamic iris diaphragm to reduce the repetition rate to a mean number of 20 pulses per second avoiding destruction of the fiber was added. The FBG was fabricated using the interference pattern of a Talbot interferometer. A cylindrical lens (focal length 221 mm) was used in front of the interferometer to increase the local intensity at the place of the fiber. The cylindrical lens was moved to scan the focus line through the full diameter with a velocity of 0.1 $\mu m/s$. Further details on the inscription of single gratings or arrays are given in Ref. [15].

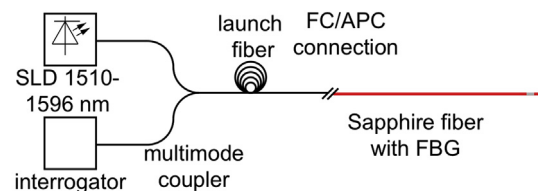


Fig. 1. FBG interrogation setup. All fiber optic components are based on standard 50 μm GI silica fibers.

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