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# High temperature sensing with single material silica optical fibers

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## ABSTRACT

We present recent developments in high temperature sensing using single material silica optical fibers. By using a single material fiber, in this case a suspended-core fiber, we avoid effects due to dopant diffusion at high temperature. This allows the measurement of temperatures up to the dilatometric softening temperature at approximately 1300°C. We demonstrate and compare high temperature sensing in two configurations. The first exploits a small section of single material fiber spliced onto a length of conventional single mode fiber, which operates through multimode interference. The second utilizes a type II fiber Bragg grating written via femtosecond laser ablation.

**Keywords:** Optical fiber sensor, microstructured optical fibers, fiber Bragg gratings, high temperature, interferometry.

## 1. INTRODUCTION

Optical fibers are useful tools for physical sensing, such as temperature, strain and pressure, due to benefits such as immunity to electromagnetic interference and ability to perform multiplexed measurements[1,2]. Of increasing interest is the use of optical fibers for very high temperature sensing due to potential markets in minerals and metals processing, engine design, aerospace and aeronautical applications, power generation, and defense.

A commonly used element for optical fiber temperature sensing is the fiber Bragg grating, which is formed by inscribing a periodic modulation in the refractive index along the optical fiber core. This causes a narrow band reflection at a particular designed wavelength, and this wavelength is sensitive to temperature due to the temperature response of the refractive index of glass. Wavelength division multiplexed (multi-point) sensing can be achieved by writing multiple gratings with different pitch along the fiber, resulting in a unique reflected wavelength for each sensor element. It is the multi-point sensing capability of FBGs, in conjunction with high accuracy and precision, high speed, reflection mode operation, and well defined and small spatial resolution, which make it the design of choice for many low temperature sensing applications. However, FBGs are traditionally written into photosensitive fibers using ultra-violet (UV) light. FBGs written in this way have a maximum operating temperature limit of approximately 500°C[2,3], due to thermal annealing out of the refractive index modifications, and commercial sensors are generally rated to 250°C or less. In addition, conventional. In addition, the guidance properties of conventional single-mode fibers change over time due to increased dopant mobility at high temperatures. For example, it is known that thermally expanded core fibers can be fabricated at temperatures from 1300°C[4]. An alternative UV inscription is the use femtosecond laser writing techniques[5-10]. By using sufficiently short duration pulses, multiphoton absorption can lead to ionization of electrons and the physical removal of material, a process known as ablation[5]. As these modifications can be written on fibers made of pure silica and are formed by physical defects there are no issues resulting from dopant dispersion and can, in principle, survive up to the point where the material softens.

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In this paper we present two different fiber sensing architectures for use as high temperature (1200-1300°C) sensors. Both techniques utilise a single material fiber, which circumvents dopant diffusion at high temperatures. The first involves using multi-mode interferometry within the single-material fiber[11], while the second utilised femto-second laser ablation[12].

## 2. SENSOR FABRICATION AND OPERATION PRINCIPLE

The optical fiber used was silica suspended-core microstructured optical fiber[13], with an outer diameter of 160 µm and a core diameter of approximately 10 µm [Fig. 1]. These fibers were then spliced to standard FC/APC connectorized single-mode fiber (SMF28) using an arc splicer (Fujikura FSM-100P).

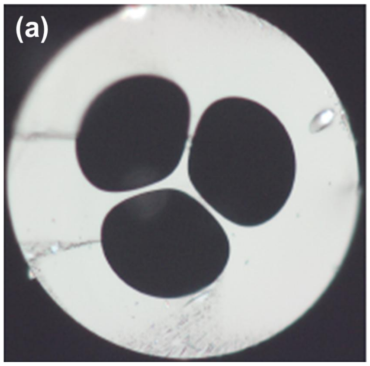

Fig. 1. Single material (suspended-core) optical fiber used for high temperature sensing.

The multi-mode interferometer (MMI) high temperature sensors[11] were fabricated by flat-cleaving a suitable length of the suspended-core fiber (SCF), typically 20-300 mm. The relatively large core diameter of the SCF means that multiple transverse modes will be excited in the core, reflect at the distal end, and then an interference spectrum will be formed when re-combined at the single-mode fiber. There is then a difference in the thermo-optic resoponse of the difference modes due to different portions of the optical mode travelling within the glass versus air (that is, differening fractions of evanescent field). Thus, changes in temperature result in changes in the phase of the resulting interference pattern.

The Bragg grating high temperature sensors[12] were fabricated by using a point-by-point technique previously developed for writing ablation gratings onto the surface of exposed-core microstructured optical fibers[14,15]. This technique involves focusing 800 nm femtosecond laser (Hurricane Ti:sapphire) pulses onto the surface of the core using a 50X long working distance microscope objective. A repetition rate of 100 Hz was used and the SCF was translated to yield second order Bragg reflections at the desired wavelength (e.g. 1550 nm).

## 2. MULTIMODE INTERFERENCE BASED SENSOR

Figure 2(a) shows the reflection spectra of a MMI sensor formed by splicing a SCF of 27 mm length to a SMF at several temperatures. Generally the interference fringes shift to the longer wavelength as the temperature increase. Since the interference spectrum is complex due to the excitation of several propagating modes in the SCF, a fast Fourier Transform (FFT) technique was used to filter out the most dominant interference and this interference is used for temperature monitoring, as shown in Fig. 2(b). The filtered interference uniformly and stably red-shifted and blue-shifted as temperature increased from room temperature to 1100°C and back down to room temperature, respectively. Figure 2(c) shows the linear fitting of the wavelength shift versus temperature, with a sensitivity of 11 pm/°C and an $R^2$ value of 0.99.

An 80-hour long temperature monitoring experiment was also carried out using the MMI sensor (not shown here). In this case, instead of measuring the wavelength shift we used the phase value at the dominant spatial frequency in the FFT spectrum as the indicator, which can be conveniently computed using a Labview program. The phase computed at the selected spatial frequency is essentially ($2\pi\Delta\lambda/FSR$) with FSR is the free spectral range. It was clear that the phase value follows the changes in the temperature, and the sensor have stable operation over a period of 80 hours.

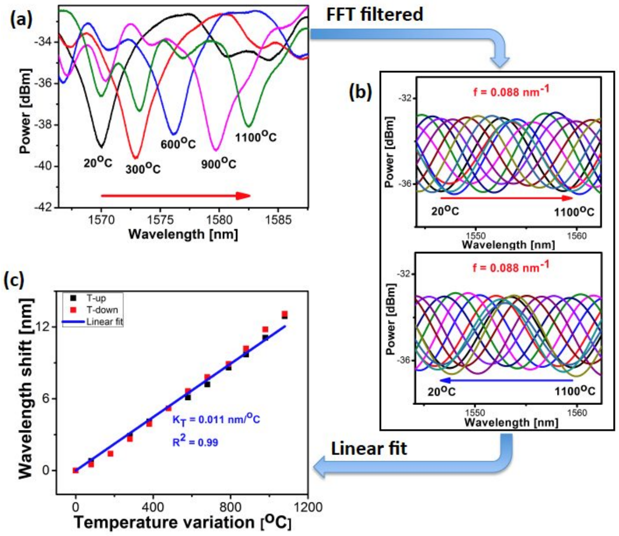

Fig. 2(a) Raw reflection spectra at different temperatures. (b) FFT filtered spectra as temperature increased/decreased over a range of 1080°C (from 20°C to 1100°C). (c) Linear fit of the wavelength shifts. Image from[11].

## 3. FIBER BRAGG GRATING SENSOR

A scanning electron microscope image of the femto-second laser ablation fiber Bragg grating on the suspended-core fiber is shown in Fig 3(a). It can be seen that the ablation points form elliptical damage lines across the core of the fiber, which is due to the focusing effect of the outer fiber cladding. It can also be seen that the points are not directly on the centre of the fiber core, however a strong grating reflection could still be measured. The reflection spectra were measured using an optical sensor interrogator (OSI, National Instruments PXIe-4844). The shift of the Bragg grating wavelength with respect to temperature up to 1000°C is shown in Fig. 3(b). The response is quadratic due to a combination of a nonlinear thermo-optic coefficient of glass at high temperatures and the increase in the fraction of evanescent field at higher temperatures due to the increased refractive index. Additional experiments have shown that the reflected spectrum is stable up to 1300°C. A wavelength division multiplexed sensor was fabricated by writing three physically separated gratings into a length of the suspended-core fiber. In this case the gratings were made 10 mm long and three different pitches were used ($\Lambda$ = 1055.7 nm, 1069.6 nm, 1083.5 nm). The gap between the gratings was 25 mm and 17 mm, respectively. The reflected spectrum recorded at room temperature is shown in Fig. 3(c).

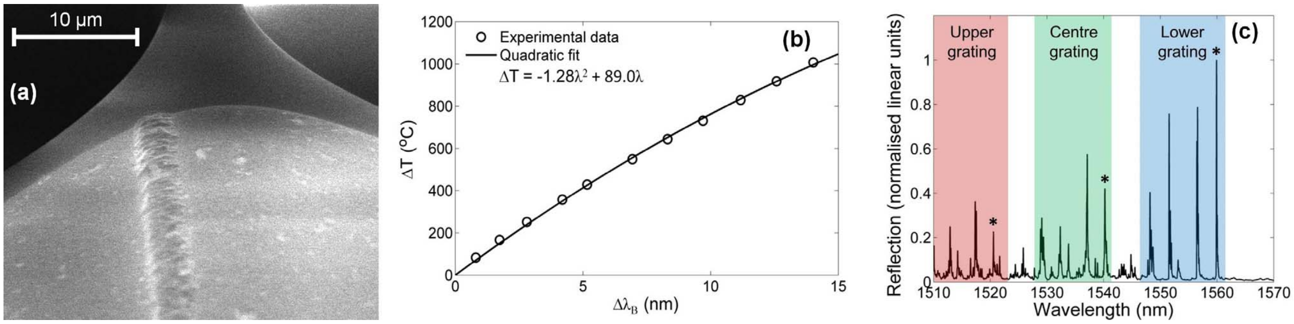

Fig. 3(a) SEM image of the fs laser ablation gratings in the suspended-core fiber. (b) Calibration curve for the shift of the fiber Bragg grating wavelength in response to temperature up to 1000°C. (c) The reflection spectra for three gratings within a single fiber. (b) and (c) are from[12].

## 4. DISCUSSION AND CONCLUSIONS

Two configurations for high temperature sensing have been demonstrated using single-material silica suspended-core fibers. The first is simple to fabricate, involving only cleaving and splicing to conventional single mode fiber and operates through multi-mode interferometry. The second technique involves writing a point-by-point femtosecond laser ablation fiber Bragg grating. The multi-mode interferometric sensor has the advantage of being simpler to fabricate, while the fs-laser written Bragg grating approach has the advantage of completely avoiding doped fiber and can be serially multiplexed. Both sensors benefit from being readily spliced to single mode fiber for easy integration with existing interrogation systems. Comparative experiments in sensitivity and upper operating limits are currently underway and will be presented.

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