Multiplexed Fiber-Optic Bragg Stack Sensors (FOBSS) for Elevated Temperatures

Fei Luo, J. Hernández-Cordero, and T. F. Morse

***Abstract*—A novel fiber-optic technique for the measurement of temperature is demonstrated. By depositing alternating quarter-wave layers of silicon nitrite and silicon-rich silicon nitrite at the end of an optical fiber, we can fabricate the equivalent of a Bragg grating of a high-temperature material to form a fiber Bragg stack sensor. When heated, the Bragg stack expands and a change in wavelength of the reflective peak is registered. Thus, the wavelength of peak reflectivity is a function of temperature. The sensors, which have previously been shown to be capable of surviving temperatures in excess of 900 °C, can be wavelength division multiplexed. Using a CCD solid-state spectrometer, we demonstrate the multiplexing of eight temperature sensors. Crosstalk effects, arising from the side lobes observed in the wave stack spectra, limit the performance of the multiplexed sensors. We show that this problem can be minimized by apodizing the Bragg stacks during fabrication. Currently, the sensor system is estimated to have a temperature resolution of 2 °C using a CCD spectrometer with a spectral resolution of 2.1 nm.**

***Index Terms*—Bragg reflectors, fiber-optic sensors, temperature sensing, thin film.**

I. Introduction

OPTICAL fiber temperature sensors have been demonstrated successfully in different configurations such as distributed, quasi-distributed, and point sensing [1], [2]. For applications in which accuracy, resolution, or dynamic range of the measurement is a concern, the use of point sensors is usually preferred. Since these types of sensors can be multiplexed in different topologies, they offer the possibility of developing systems that can monitor several locations using a single light source, a detector, and a signal processing system, which greatly reduces the cost of the sensor system [3].

The use of UV-written fiber Bragg gratings for fiber-optic sensor applications has been reported extensively [4]. This kind of grating, however, is not suitable for temperatures in excess of 500 °C, and thus for measuring elevated temperatures a different approach has to be followed. As we demonstrated previously, quarter-wave stacks of high-temperature materials fabricated at the end of an optical fiber can be used for the measurement of elevated temperatures [5]. Since the information obtained from these sensors is wavelength encoded, a compact wavelength division multiplexed measuring system can be implemented with these fiber-optic Bragg stack sensors (FOBSS). Besides being highly scalable, the system offers the possibility of having all the electronics at a remote location from the region to be monitored, which is an attractive feature for several military and industrial applications.

In this letter, we report on the first attempt to multiplex eight temperature FOBSS using a CCD solid state spectrometer. The spectral characteristics of the sensors and their response to temperature after exposing them several times to changes up to 800 °C are shown. Crosstalk effects, originated from the side lobes of the wave stacks, are shown to affect significantly the performance of the multiplexed system. To overcome this, it is demonstrated that a considerable reduction of the side lobes can be achieved upon apodization of the wave stack, and hence crosstalk effects can be minimized.

II. Sensor Characterization

The fabrication of the sensors is based on the deposition of alternated layers of silicon nitrite and silicon-rich silicon nitrite. Using an *in situ* thin film monitoring system developed in our laboratory, we are able to measure the thickness of the material deposited at the end of the optical fiber [6]. Hence, we can deposit the alternating layers using a CVD reactor and monitor the formation of the 1/4 wave stack at the end of the fiber. This wave stack functions exactly as a UV-written fiber Bragg grating in that there can be high reflectivity over a relatively narrow band of wavelengths, and upon changes in temperature, this reflection peak shifts. The FWHM of the reflective "Bragg stacks" is approximately 15 nm, and all of them have been fabricated on standard 62.5/125 polyimide coated multimode fiber. Since the wave stacks are fabricated using silicon nitrite, a high temperature material with a melting point of the order of 1900 °C, the limitation of the sensors is mainly associated with the structural integrity of the silica. The silica will maintain its structural integrity at temperatures below 1000 °C–1100 °C, and at temperatures somewhat in excess of this the degradation occurs over a time period of a few hours.

Preliminary results reported in [5] showed that it is possible to make laboratory measurements of temperature in excess of 1100 °C using an FOBSS. Furthermore, a more realistic demonstration was carried out in battle simulation tests conducted on the U.S.S. Shadwell, a fire research vessel managed by the Naval Research Laboratory. One of the sensors was exposed to fire eight times, and for half of these tests, the temperature exceeded 800 °C. Multiplexing of two sensors was demonstrated using a solid state spectrometer (Ocean Optics), and the main limitations of the systems were imposed by crosstalk, originated from

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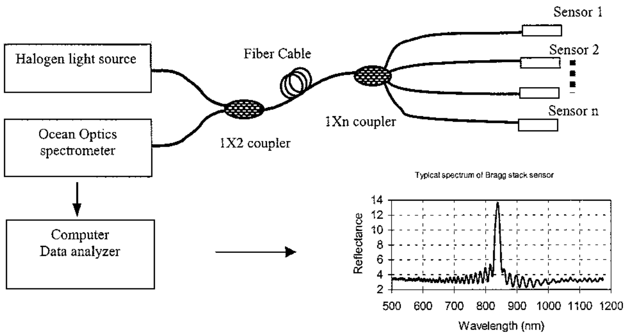

Fig. 1. Schematic of the wavelength division multiplexed system for measuring elevated temperatures. The inset shows a typical reflection spectrum from an FOBSS used in the system.

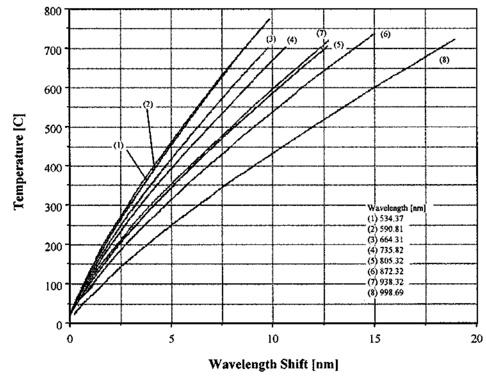

Fig. 2. Calibration curve for eight FOBSS.

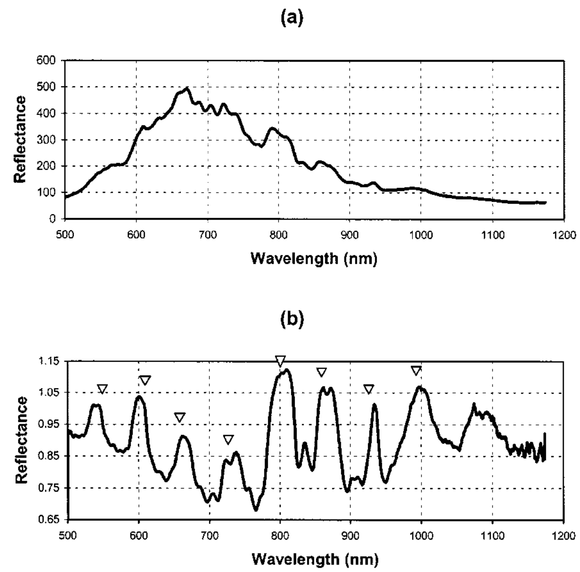

Fig. 3. Reflected signal from the sensor array (a) before and (b) after signal processing.

the overlap between the main reflective peak of the wave stacks and the side lobe of the other wave stack.

Further characterization of the sensors has been carried out in our laboratory. The sensors were exposed several times to temperature changes of up to 800 °C by placing them in an electric furnace controlled with a rheostat. A thermocouple was used to calibrate the wavelength shifts registered by the computer. The software, which uses a correlation algorithm, was developed using Lab View and it was designed to trace the shifts in wavelength of the reflection peak of the FOBSS. Currently, the sensor system is estimated to have a temperature resolution of 2 °C using a CCD spectrometer with a spectral resolution of 2.1 nm (Ocean Optics).

To evaluate the multiplexing capabilities of the system, eight Bragg stacks sensors were fabricated at different wavelengths. A schematic of the wavelength-division-multiplexed system is shown in Fig. 1, with an inset of a typical spectrum of an FOBSS. Stabilization of the reflection spectrum was achieved by annealing each sensor before calibration. The temperature response of the sensors can be seen in the calibration curves shown in Fig. 2. The nonlinear response of the sensors to changes in temperature is evident in this figure. Each calibration curve was fitted with a third-order polynomial and the resultant coefficients were incorporated into the software. Hence, a temperature reading corresponding to a wavelength shift was obtained for the sensors. Since each FOBSS was fabricated to provide a reflection peak at different wavelengths, the polynomial coefficients were slightly different. However, as shown in Fig. 2, all of them showed a similar response.

As shown in Fig. 1, all the sensors were interrogated simultaneously using a single channel of the CCD spectrometer and a tungsten halogen white light source. The sensors were multiplexed using an array of 1×2 multimode couplers and linked to the light source and the spectrometer through a 100-m fiber-optic cable. The original spectrum registered by the spectrometer is shown in Fig. 3(a), which evidently yields little information about each sensor. This is due to the nonflat emission spectrum of the light source, the spectral response of the CCD array, the spectral dependence of the fiber loss, difference in reflectance for each wave stack, and the side lobes observed in some of them. To overcome this problem, a special normalization algorithm was incorporated into the software. The spectrum obtained after processing is shown in Fig. 3(b), in which the location for each of the sensors at room temperature is indicated. Although the software effectively reduces the effects of using wave stacks with different reflectivities, it is evident that crosstalk effects are not eliminated. Since the side lobes observed in some of the FOBSS can overlap with the spectral region covered by another sensor, signal processing in this case is of little help. The effects of crosstalk were observed by exposing all the sensors to temperatures of up to 800 °C and removing each of them one at a time. The wavelength shift of the side lobes due to the change in temperature affected the reading of the other sensors. Thus, reduction or elimination of crosstalk relies only on the effective suppression of the side lobes during the fabrication process of the wave stacks.

III. "Bragg" Wave Stack Apodization

It is well known that the optical properties of a fiber grating are essentially determined by the variation of the index change along the fiber axis [7]. This fact has allowed for the design and fabrication of short- and long-period fiber gratings with adequate spectral responses for several applications. It has been demonstrated, for

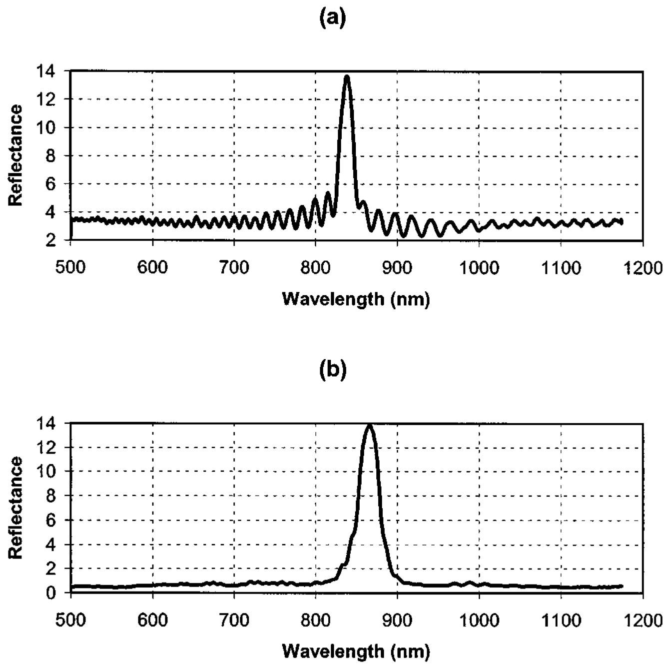

Fig. 4. Spectra for (a) a regular and (b) an apodized "Bragg" stack.

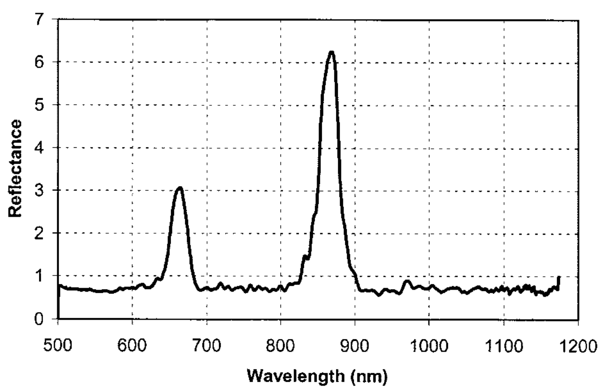

Fig. 5. Spectrum of two apodized multiplexed FOBSS.

example, that apodization of the grating (i.e., to impose a smooth modulation envelope on the index change along the fiber) reduces the side lobes observed in fiber grating spectra.

Following a similar approach, the spectral response of two wave stacks was tailored during fabrication so as to reduce the side lobes. Since the fabrication process involves the use of an *in situ* thin-film monitoring system, the wave stack spectrum can be monitored continuously during the deposition of each layer. As explained in [6], the refractive index of each layer of the deposited material can be varied upon changing the flow of gases into the reaction chamber of the CVD system. Hence, the refractive index of the final layers of the wave stack was varied until the side lobes in the spectrum were reduced to a minimum. Fig. 4(a) and (b) shows the effects of apodization of the "Bragg" stack achieved with this procedure. For these experiments, the gas flow was adjusted manually for each of the final layers of the wave stacks. We have recently acquired a computer driven flow controller and efforts to fabricate computer optimized "Bragg" wave stacks are underway.

The spectrum obtained using two apodized wave stacks with a resolvable spectral space is shown in Fig. 5. Crosstalk effects using these two sensors were evaluated by placing them into the furnace, raising the temperature to 800 °C and finally letting the temperature decrease at a slow rate. At some arbitrary moment during this process, one of the sensors was removed from the furnace. This allowed us to verify that the reading from the remaining wave stack was not affected by the temperature changes experienced by the other sensor. The maximum change in the temperature reading due to crosstalk was estimated to be 2 °C over the full temperature range of 800 °C. Although this value can change depending on the location of the reflection peak of one sensor with respect to the other, this is a small fraction of the total temperature range covered by the sensors. Despite using only two wave stacks to demonstrate the effects of apodization on crosstalk, we believe that these results can be generalized for multiplexing at least eight or ten sensors.

IV. Conclusion

We have demonstrated a scalable system of multiplexed sensors for the measurement of elevated temperatures. By depositing alternated layers of stoichiometric silicon nitrite and silicon-rich silicon nitrite on the tip of a multimode optical fiber, quarter-wave stacks with reflection peaks at specific wavelengths can be fabricated. Although these wave stacks have a wider spectral response than that obtained with UV-written fiber Bragg gratings, it is possible to multiplex at least eight sensors by means of a white light source and a solid state spectrometer. The sensor system is estimated to provide a temperature resolution of 2 °C by using a CCD spectrometer with a spectral resolution of 2.1 nm. Crosstalk effects were confirmed to be significant when multiplexing eight sensors. These arise from the side lobes observed in the "Bragg" wave stacks, which can have different spectral overlapping with the main peaks of the other sensors used in the array. Minimization of crosstalk effects was achieved by apodization of the sensors. This was done during the fabrication process by varying the refractive index of the final layers of the wave stack. A significant reduction of crosstalk effects was demonstrated using two apodized "Bragg" wave stacks, and it is expected that similar results will be obtained with arrays of eight or ten sensors.

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