Fiber Bragg grating sensors in industrial heating systems

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Abstract

This paper presents the sensor development and calibration stages of a novel monitoring platform that is designed for industrial microwave ovens. The monitoring unit is based on fiber Bragg grating sensors providing 2D quasi-distributed temperature measurement inside a high microwave power environment. We discussed the main design issues and experimentally demonstrated the sensor calibration set-up. Repeatability measurements highlighted a standard deviation on the sensitivity values smaller than 0.4 pm/°C.

1. Introduction

High safety level, sustainability, and reduced energy consumption are the major concerns in today's industrial applications. The food industry represents one of the most strategic areas that determine the welfare of countries.

Food safety is a fundamental requirement of the world that is facing a range of serious ecological and public health threats. The food drying process is one of the most critical sectors of the food industry. Aflatoxins present in dried fruits and edible nuts are known to be responsible for 30% of liver cancer cases, affecting 25% of the World's food corporations [1]. According to [1], it is estimated that 1 in 10 people fall ill after eating aflatoxin-contaminated food, resulting in 420.000 deaths per year.
Revenue generated from the global dried fruits market has been estimated to be valued at around US$ 7,255.4 Mn in 2018, which is projected to increase at a CAGR of 5.9% during the forecast period (2018-2026). Any health concern (e.g., Aflatoxins) that cannot be detected/ avoided along production stages may lead to a tremendous loss in business for the corporations. We can mention not only direct financial losses due to product loss but also indirect financial losses due to bad reputation. These arguments have been gaining importance as the warranty on the sustainability and quality of the final product becomes a deciding factor in the competitive marketplace.

Industrial Microwave Ovens have been gaining great attention as a food drying tool to reduce microbial load and increase shelf life. Integration of novel, sophisticated and precise sensors into these Microwave Ovens will significantly enhance the whole process of making safe and sustainable food.

Despite the advantage of fast and efficient heating, microwaves do not have uniform homogeneous heat distribution due to the nature of the microwave heating systems. Unlike conventional furnaces, they heat only the materials (water) that contain polar molecules (not the entire cavity). Hence, depending on the microwave frequency, non-heating points, which are described as blind spots, occur in the cavity.

Detection of these blind spots is essential for processes that require precise heating. If blind spots are properly detected, their effects can be minimized by changing the cavity design. With the help of fiber optic sensors, the temperature distribution inside the cavity can be detected, which is otherwise a difficult task using conventional sensors (prone to electromagnetic interference).

Optical fiber optic sensors represent a powerful class of alternative technologies that can be used to develop smart food monitoring systems. Their advantages can be listed as their low weight, small dimensions, remote operation, and immunity to electromagnetic interference [2]. Among all fiber optic sensors, those based on fiber Bragg gratings (FBGs) have a significant potential. FBGs provide the intrinsic capability of measuring several parameters, such as temperature and strain; thanks to their spectral shift as a function of the parameters to be measured. The first commercial FBGs were manufactured in the mid-1990s [3]. Since then, in addition to their substantial utilization in the telecommunication industry, parallel efforts have also been carried out to exploit the key features of FBGs for sensing purposes.

Nowadays, the sensing sector is benefiting from the great potential of FBG-based sensor systems. Their acceptance is continuously increasing. For sensing applications, FBGs offer the following advantages: they are cost-effective and mass-producible devices providing self-referencing and wavelength-encoded linear response so that they are robust to unwanted optical power fluctuations. Furthermore, these devices allow high degrees of multiplexing (wavelength-, time- or spatial-division), and therefore enable multi-point sensing schemes where many gratings can be placed within a single optical fiber. With standard commercially available read-out techniques, tens of sensors can be cascaded and simultaneously interrogated along a single optical fiber.

This paper presents the main design issues of a temperature monitoring system developed for industrial microwave ovens.

It consists of FBG sensor arrays in a grid and a sensor interrogator unit. Experimental results of the sensor test and calibration set-up have been reported. Practical issues that require further investigations together with future perspectives have also been presented.

2. Experimental Set-up for Sensor Calibration

First, arrays of fiber Bragg grating (FBG) sensors have been developed allowing to provide a mapping of the temperature inside the oven. We then developed an experimental set-up at IZTECH, Fiber Optic Metrology and Sensor Applications Laboratory (FiSENS-Lab) to calibrate the sensors in the temperature range of the application (between room temperature up to 70 °C) and determine the temperature sensitivity. This process is very useful for correlating the wavelength shift undergone by the grating with the actual temperature measured in the environment. Theoretically, FBG temperature sensitivity can be defined as the ratio of Bragg wavelength shift $\Delta\lambda$ to the temperature change ΔT and is given by the following formula where λ is Bragg wavelength, α is the thermal expansion coefficient and ξ is the thermooptic coefficient [4].

$$\Delta\lambda/\Delta T = \lambda(\alpha+\xi) \quad (1)$$

In a uniform FBG where the grating period Λ and effective refractive index n_{eff} is constant, Bragg wavelength is expressed as:

$$\lambda = 2n_{eff}\,\Lambda \quad (2)$$

Noting the definitions of thermal expansion and thermooptic coefficients such as:

$$\alpha = \Lambda^{-1}\mathrm{d}\Lambda/\mathrm{dT} \quad (3)$$

$$\xi = n_{eff}^{-1}\mathrm{d}n_{eff}/\mathrm{dT} \quad (4)$$

Substituting equations (2)-(4) in equation (1) yields the sensitivity in terms of the rate of change of n_{eff} and Λ with respect to temperature:

$$\Delta\lambda/\Delta T = 2(n_{eff}\,\mathrm{d}\Lambda/\mathrm{d}T+\Lambda \mathrm{d}n_{eff}/\mathrm{dT}) \quad (5)$$

As represented in Figure 1, after having connected one of the fiber ends to the interrogator device, we placed the fibers in a laboratory oven (one of the side walls has been drilled to bring out the fiber optic connectors towards an interrogation unit), which allows us to calibrate and test the FBG groups previously inscribed. Thanks to its preconditioned heating ramp, a fairly uniform temperature is guaranteed inside the enclosure.
Inside the oven, there are two thermocouple probes (one for the oven's self-regulation, the other close to FBGs to measure the reference temperature). The Bragg grating interrogator, based on a broadband source and a spectrometer, can measure up to 40 sensors on a single channel over a range of wavelengths between 1510 and 1590 nm.

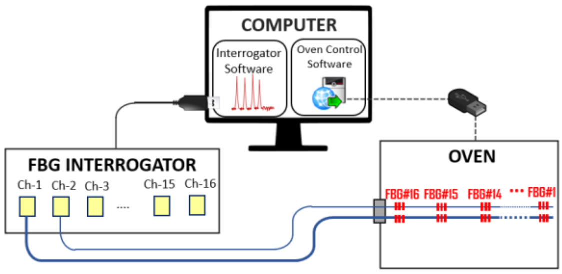

Fig. 1. Schematic representation of sensor calibration set-up

2.1. Sensor manufacturing

FBG sensors were inscribed by Lloyd technique (B-Sens Lab.). This decision was taken mainly due to the wavelength tuning capability of this technique, which is required for the temperature sensor grid (tens of different FBGs on the same fiber with different Bragg wavelengths). This technique uses a 244 nm continuous laser (UV). An interference pattern is created by a division of the laser beam and a slightly different optical path induced by the reflection of the beam on a mirror. This optical path difference will induce interference at the fiber, allowing the inscription of the Bragg grating in the core of it. By slightly modifying the orientation of the mirror, we modify the optical path difference, inducing different interferences and therefore Bragg gratings having different reflection spectra. The length of each sensor is equal to 3 mm. The optical fiber used is SM1500 (4.2/125) from FiberCore with acrylate coating.

Ruggedized connectors and special packaging were also applied, enhancing the sensors' robustness in the oven environment.

The packaging should be a material that does not affect the electromagnetic field created by the microwave oven. Therefore, we have limited ourselves to certain packaging that is inert to electromagnetic waves. PTFE, ETFE, and Hytrel were chosen for the test phase. All packaging options tested are shown in Table 1 together with their main characteristics. PTFE was selected to be implemented for the rest of the experimental work.

Table 1. Specifications of different packages

	Temperature interval	Internal/external diameter (µm)
PTFE polytetrafluoroethylene	-200 °C to 200 °C	560/1160
ETFE ethylene tetrafluoroethylene	-55 °C to 150 °C	500/900
Hytel thermoplastic elastomers	-40 °C to 70 °C	>400/900

2.2. Main design concerns

Effect of microwave on the fiber and its coating: A literature search has been conducted to check possible negative effects of electromagnetic radiation in the frequency range of interest on the sensor materials and performances. An aging phenomenon of silica optical fibers is reported in [5] related to water activity, which might be accelerated when exposed to microwaves (supplementary energy). Nevertheless, no adverse effect is expected for our application as the sensors are neither severely bent nor directly exposed to water in the cavity.

Measurement time: The sensor's response (FBG) is almost instantaneous, and the total time required to interrogate the whole sensor array is a few seconds (signal processing). Moreover, the measurement time is independent of the number of interrogated gratings and temperature measurement range. However, the reference thermocouple response time is limited to one measurement per minute, which introduces the necessity to equalize the number of thermocouple data points by resampling.

Number of addressable sensors: We use wavelength-division multiplexed (WDM) sensors, which are the most commercially encountered systems. In these systems, a unique range of operating wavelengths (under identical temperature conditions) is dedicated to each grating of the concatenation. Therefore, the number of sensing points is directly limited by the spectral ranges of the source (and the detector) together with the wavelength spacing between two gratings.

The temperature range to be measured is a maximum of 80°C. Even if we take the temperature range of 100°C (by adding 20°C of security margin), the wavelength range required by a single sensor is calculated as 1170 pm (1.17 nm) using a sensitivity value of 11.7 pm/°C.

The interrogator that we use in the calibration set-up, based on a broadband source and a spectrometer, can measure up to 40 sensors on a single channel over a range of wavelengths between 1510 and 1590 nm. This is largely sufficient for our application, where 16 to 20 FBGs in a single fiber are enough to obtain an adequate temperature map.

Cross-correlation of FBG response to the temperature and strain. The Bragg wavelength shift associated with an external perturbation is produced by both temperature and strain. It is therefore required to discriminate the strain and the temperature effects when only one perturbation is of interest (temperature in our case). It is necessary that the fiber, and more particularly the FBG, be free of axial strain to measure a temperature. For the goal of having a map of the temperature inside the oven, it is important to identify the right packaging which does not disturb the electromagnetic distribution inside the oven but also which makes it possible to obtain a viable temperature measurement. To do this, the team packaged several fibers so that the FBGs inscribed in their cores remain strain-free (cf. Section 2.1).

Mechanical design of FBG entrance and exit positions: The determination of FBG entrance and exit positions, cable dimensions, and spacing between temperature sensor nodes are critical aspects of the final implementation of FBGs inside the cavity. Figure 2 shows the 3D image of our design, where 16 fibers (including FBG sensors) are organized in a bundle structure.

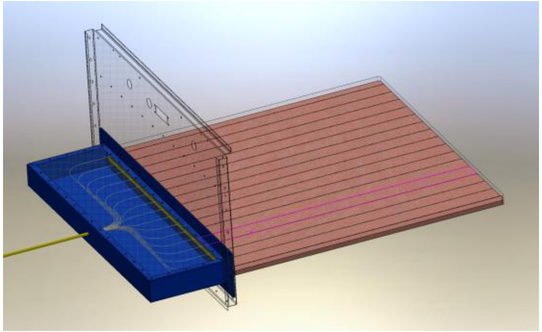

Fig. 2. Ingress/ egress of the FBG's and wiring bundle

3. Results and Discussions

3.1. Sensitivity measurements and repeatability tests

The shift in the reflection peak of the FBG for a unit change in temperature can be defined as the sensitivity of the FBG sensor. Several tests have been conducted on the FBG arrays to determine the mean and variance of the sensitivity values.

During the calibration process, two types of FBG arrays (with and without packaging) were compared. Two arrays are listed in Table 2. Since the FBGs in arrays #1 and #2 have similar Bragg wavelengths, as shown in Figure 3, the effect of the packaging was investigated by observing their response under the same oven conditions.

Table 2. Sample FBG Arrays used in calibration experiments

Array No	Number of FBGs	Package
#1	16	No
#2	16	Yes (PTFE)

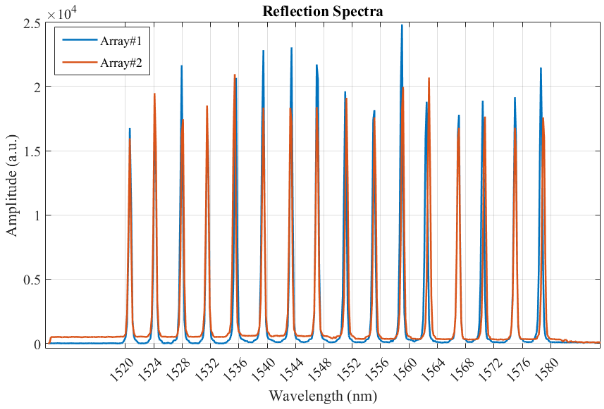

Fig. 3. Reflection spectra of the FBG arrays

16 FBGs of arrays #1 and #2 were aligned and placed side by side in the oven. One end of both the arrays was connected to the interrogator, and a temperature ramp from 20 to 70 degrees was applied by the oven for approximately 180 minutes. This experiment was carried out four times (cf. Fig. 4), and the recorded Bragg wavelengths by the interrogator, along with the measured temperature by the thermocouple, were processed on MATLAB to obtain the sensitivity of each FBG. The resulting mean and standard deviation of the sensitivities are represented by the error bar in Figure 5.

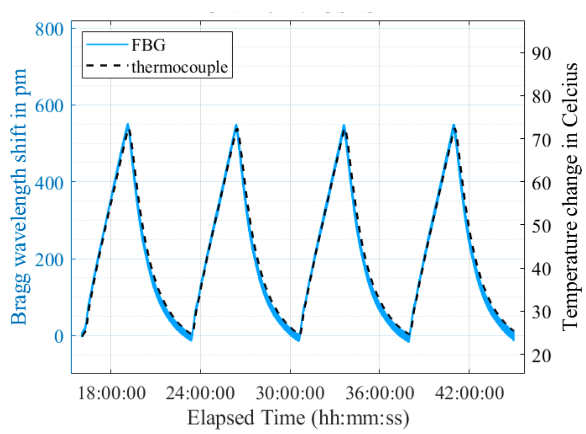

Fig. 4. Sequential heating cooling experiment

The temperature sensitivity of an FBG arises from the refractive index change (thermal dependence of the refractive index) and grating period variation (thermal expansion coefficient of the optical fiber) as demonstrated in equation (5). Average sensitivity values measured during calibration tests vary between 11 pm/°C and 11.7 pm/°C.

One should note that FBG sensitivity depends on the type of optical fiber dopants. SM1500 is a high-doped Ge fiber. This is why the sensitivity values for both arrays are slightly higher than that of the value reported in the literature for standard SMF (10 pm/°C).

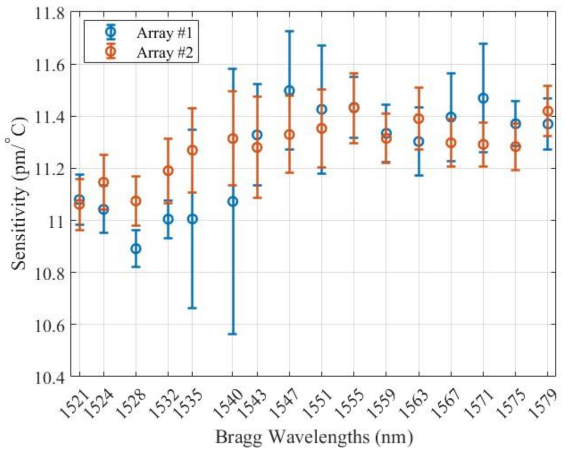

Fig. 5. Mean and standard deviation of the FBG sensitivities in unpacked (blue) and packed fibers (red)

As can be interpreted from Figure 5, package has a little effect on the mean sensitivity of the FBGs. However, it reduces the standard deviation, as clearly seen in the FBGs with Bragg wavelengths of 1535 and 1540 nm. The maximum standard deviation of the sensitivities belonging to Array #1 is approximately ± 0.5 pm/°C, double of the one belonging to Array #2. The reason for the high standard deviation in Array #1 may be the vibration due to heat-induced loosened adhesive tapes that cannot trap fiber well anymore. The package protects FBGs from such vibrational movements in Array #2.

After observing the advantage of the packaging, Array #2 was subjected to a sequential heating-cooling experiment, and sensitivities in the heating and cooling ramps were compared to each other as shown in Figure 6.

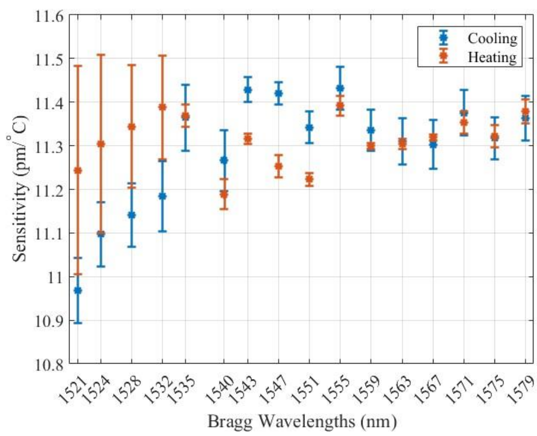

Fig. 6. Heating vs cooling

The thermocouple collects data 60 times slower than the FBG interrogator due to its response time. The missing temperature data between consecutive thermocouple measurements are filled by resampling the thermocouple data in a 60 times higher sampling frequency. When the speed of change of the real temperature is more than the thermocouple sampling frequency, the resampled temperature points may have an estimation error. Since the thermocouple samples are not the same in each cycle, the resulting resampled temperature arrays are also different, which causes the estimation error in resampling to vary from cycle to cycle.

The higher standard deviation in cooling cycles in Figure 6 can be related to the more varying estimation error in the resampled thermocouple data.

3.2. Nonlinearity in sensitivity measurements

During calibration measurements, some non-linear FBG responses have been observed in some FBG arrays. Figures 7 and 8 represent two example cases where one can observe a sensitivity increase of all the FBGs in the array starting from about 70 °C (Fig.7) and 50°C (Fig. 8).

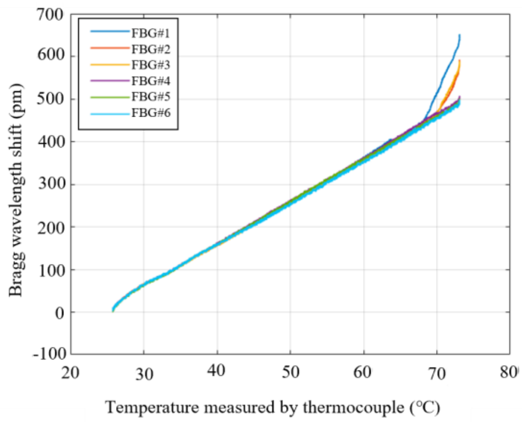

Fig. 7. Bragg wavelength shift versus applied temperature. An example case where a nonlinear behavior is observed above 70°C.

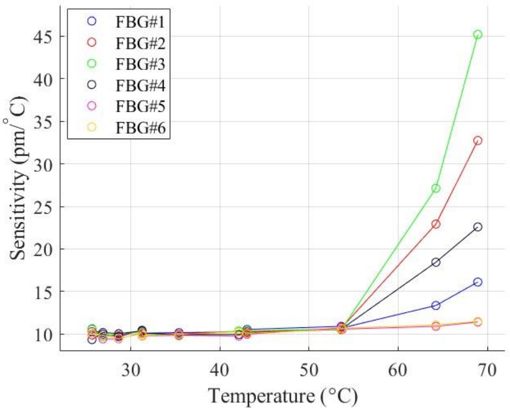

Fig. 8. Sensitivity versus applied temperature. An example case where a nonlinear behavior is observed above 50°C.

After a literature review, this behavior might be attributed to the thermal expansion of the PTFE (Polytetrafluoroethylene) package. The coefficient of thermal expansion (CTE) has been reported to influence the sensitivity when other physical and mechanical parameters are maintained constant [6]. The CTE value is reported as much higher for polymers than it is for metals [6]. The CTE of PTFE itself varies with temperature, which is why we can predict a sudden nonlinearity in the temperature dependence of the reflected wavelength, in an experimental scenario.

We also observed through experiments that nonlinear behavior does not come out when the FBGs in the array are interrogated one by one (ensuring no bending).

Therefore, we don't expect any problem in terms of CTE in the microwave implementation, as all the fibers will be used in straight lines. Still, the reasons for experimental results like those in Figures 7 and 8 will continue to be studied. The diameter of the PTFE packaging would be another parameter to investigate.

4. Conclusions

Industrial microwave ovens are designed to heat up the product inside the oven, efficiently, fast and homogeneously. In addition to the food industry, there are many other application areas of microwave heating systems such as drying of peroxide/explosive materials, tempering of cosmetic textures, heating, and drying of ceramic goods, heating/melting of polyamide used in the medical industry, drying of adhesive coatings on fast paper webs, roasting of coffee-beans.

Homogeneous heating is essential for all these applications. Microwaves can easily form standing waves inside the cavity, and this causes cold spots on the product. These cold spots cannot be heated up to the desired level and can cause insufficient output product quality.

This paper presents the sensor development and calibration stages of a novel monitoring platform that is designed for industrial microwave ovens. The monitoring unit is based on fiber Bragg grating sensors providing 2D quasi-distributed temperature measurement inside a high microwave power environment. Other electrical sensors cannot operate inside microwave cavities due to high electromagnetic interference.

Sensor fabrication, sensor test & calibration, and mechanical design steps have already been realized and reported in this paper. Effect of PTFE packaging is observed as an advantage of protecting the FBGs from vibration. However, it can induce nonlinearity in the FBG response in certain conditions which will be investigated in more detail. The number of cascaded gratings and the distance between them have been optimized according to the dimensions of the oven. The next step of the work will be to implement fibers packaged to carry out tests under microwave radiation.

7. Acknowledgement

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