

Research Article

Fibre Tip Sensor with Embedded FBG-LPG for Temperature and Refractive Index Determination by means of the Simple Measurement of the FBG Characteristics

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A novel optical fibre sensing system based on a hybrid long period grating (LPG) and Bragg grating (FBG) configuration is proposed and demonstrated experimentally. The hybrid configuration, which uses the difference in temperature and refractive index (RI) different response of a Bragg grating and a long period grating, makes it possible to discriminate simultaneously the temperature and the refractive index of different aqueous solutions. RI (1.33 RIU–1.40 RIU) and temperature (21°C–28°C) working ranges have been experimentally determined. Experimental results show that the maximum accuracy in the refractive index measurement (0.004 RIU) with temperature compensation has been achieved within the working ranges.

1. Introduction

Owing to their many advantages, such as compactness, electromagnetic interference immunity, high sensitivity, and multiplexing capabilities, optical fibre sensors (OFSs) based on gratings have attracted considerable interest in the context of chemical and biochemical sensing [1].

According to the grating period, fibre gratings can be classified into short period gratings (or fibre Bragg gratings, FBGs, period in a range of hundreds of nanometres) and long period gratings (LPGs, period in a range of hundreds of micrometres).

FBGs induce the coupling of the fundamental core propagating mode to its respective counter propagating mode, while LPGs are characterized by mode coupling between the propagating core mode and copropagating cladding modes which gives rise to a series of attenuation bands in the transmission spectrum centred at discrete wavelengths that verify the matching condition of each coupled cladding mode [2, 3]. In the last case, the resonance wavelengths of the LPG coupled cladding modes depend on the external refractive index [4] and any modulation of the core and cladding

guiding properties will modify the spectral response of the LPG.

Grating based sensors have been proposed for a wide range of applications including measurements of strain, temperature, pressure, and refractive index (RI) and many examples are reported in literature. However, in the context of sensing, one of the most significant limitations is the sensitivity of both grating structures to different parameters: for FBGs strain and temperature and for LPGs strain, temperature, and external refractive index.

In order to overcome the strain-temperature cross sensitivity effect and to make possible multiparameter measurements, several techniques and configurations were thoroughly investigated and proposed in literature. These solutions include configurations based on dual-wavelength superimposed gratings [5, 6], tilted FBG [7], FBGs written in fibres with different diameters [8], and hybrid LPG/FBG [9].

To determine separately the temperature and the refractive index of different aqueous solutions, many configurations have been proposed, including Mach-Zehnder interferometer realized on tapered optical fibre [10], hybrid cascaded LPG/FBG configuration integrated with a thermostabilized

flow cell [11], and hybrid LPG/FBG structure UV-inscribed in a D-fibre [12].

In this paper we present and demonstrate experimentally a new optical fibre sensor which makes it possible to simultaneously discriminate between temperature and refractive index of different aqueous solutions by means of a LPG and a FBG written in the same optical fibre section, by simply measuring both the wavelength shift and the amplitude modulation of the peak corresponding only to the FBG resonance. This approach has been already proposed [13], but only a theoretical simulation is reported and at our knowledge it is the first time that this method has been experimentally verified.

The design and the characterization of the hybrid optical sensor are described and the results show the possibility to obtain an accurate value of the refractive index of different aqueous solutions making a temperature correction by monitoring only the Bragg reflected spectrum in terms of reflected power changes and resonance wavelength shifts.

In particular, while the Bragg resonance wavelength shifts are just related to temperature variations, both temperature and external refractive index changes have effect on the Bragg reflected spectrum.

The experiments demonstrate that good accuracy, simple structure, and easy operation for correcting temperature effect are the advantages of the proposed device.

2. Materials and Methods

2.1. Principle of Operation. Since the LPG is inherently sensitive to both RI and temperature, one of the most important issues of the LPG based sensor is the discrimination of those two parameters. A hybrid structure of LPG and FBG is a straightforward solution to facilitate simultaneous measurement of such parameters, since the FBG's response is not affected by changes in the surrounding RI.

A schematic diagram of the proposed structure is shown in Figure 1(a). The sensor probe consists of a LPG followed by a FBG, both permanently inscribed on the same optical fibre.

In particular, the FBG must be designed to be spectrally located on the edge of the LPG's response and the final transmission spectrum must have the shape shown in Figure 1(b). The fact that both gratings resonance peaks occupy the same bandwidth is the key point of the proposed configuration. Moreover, the spectral position and the spectral distance between LPG and FBG influence the RI and T working range of the sensor.

The hybrid LPG-FBG structure is sensitive to any changes in the temperature and the refractive index of the surrounding medium that leads to a shift of both grating resonance wavelengths and thus to a modification of the transmission spectrum reported in Figure 1(b).

These changes induced by temperature and external refractive index perturbations on both grating resonance wavelengths could be expressed by the following equations:

$$\begin{aligned} \Delta\lambda_{\text{FBG}} &= g(\Delta T) = s_T \Delta T, \\ \Delta\lambda_{\text{LPG}} &= g'(\Delta T, \Delta n) = s'_T \Delta T + f(\Delta n), \end{aligned} \quad (1)$$

where s_T and s'_T are, respectively, the FBG and LPG temperature coefficients induced by a temperature change ΔT , while $f(\Delta n)$ is a nonlinear function that expresses the LPG sensitivity to the external RI (Δn). In particular, when both the refractive index and the temperature of the solution increase, the LPG's resonance peak will move toward shorter wavelengths (blue shift). On the contrary, the FBG's peak will move toward longer wavelengths (red shift) as temperature increases and will be unchanged for external refractive index changes.

To clarify the working principle of the sensor, we can consider Figure 2, where separate qualitative analysis of the effects due to temperature as well as refractive index on the transmission and reflected spectrum is reported. Any changes in the surrounding refractive index (Figure 2(a)) determine only the shift of the LPG resonance wavelength which leads to a simple amplitude modulation of the Bragg reflected spectrum. On the contrary, when temperature changes occur, the resonance wavelength of both gratings is shifted (Figure 2(b)) and this leads not only to an amplitude modulation of the Bragg reflected power, but also to a Bragg resonance wavelength shift. Therefore, the T and RI information can be deduced by monitoring only the Bragg reflected spectrum in terms of Bragg wavelength shift and reflected power changes.

As will be described and experimentally demonstrated in the next section, the behaviour of the sensor could be described by the following equations:

$$\Delta\lambda_{\text{FBG}}(\Delta T) = s_T \Delta T, \quad (2)$$

$$\Delta P_{\text{FBG}}(\Delta T, \Delta n) = \alpha_T \Delta T + f(n). \quad (3)$$

As shown in (2), the FBG's wavelength is exclusively influenced by temperature changes and this relationship can be used to separate the T and the RI effects. Substituting (2) in (3), it is possible to figure the relationship between Bragg's reflected power, the wavelength shift, and the RI changes. One has

$$\Delta P_{\text{FBG}} = \gamma \Delta\lambda_{\text{FBG}} + f(n), \quad (4)$$

where $\gamma = s_T/\alpha_T$ is the sensor thermal sensitivity.

Both relationships described by (2) and (4) are, respectively, linear within a temperature and a wavelength range. The width of these intervals is related to the mutual position of the gratings on the transmission spectrum.

As a matter of fact, the choice of the temperature as well as wavelength working ranges of the sensor depends on the proper choice of the gratings location on the transmission spectrum: the more grating's peaks are distant on the transmission spectrum, the smaller is the range of the linearity response.

Through (4), the function $f(n)$ related to the surrounding RI can be obtained as follows:

$$f(n) = \Delta P_{\text{FBG}} - \gamma \Delta\lambda_{\text{FBG}}. \quad (5)$$

As shown by (5), the wavelength shift induced by temperature is used for the temperature compensation.

Finally, by inverting the function $f(n)$ obtained from (5), the temperature compensated RI value is obtained.

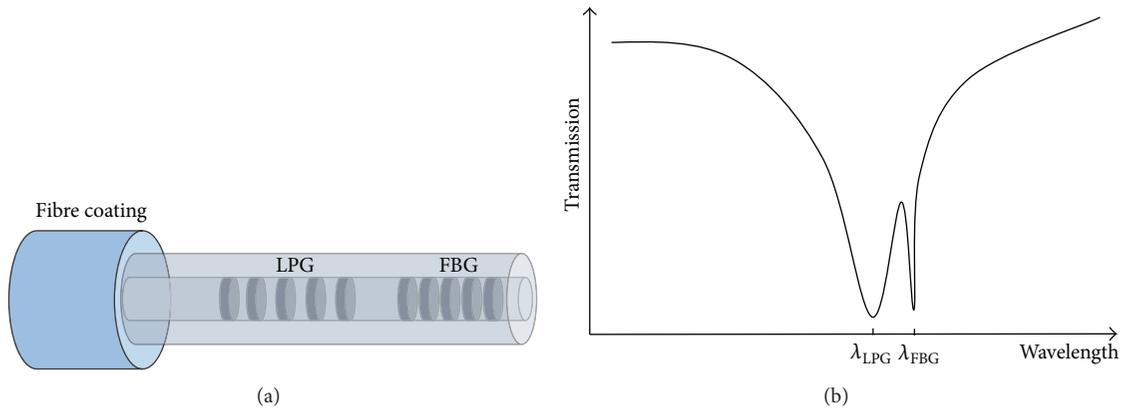


FIGURE 1: (a) Schematic of the LPG/FBG hybrid sensor; (b) transmission spectrum of the proposed sensor.

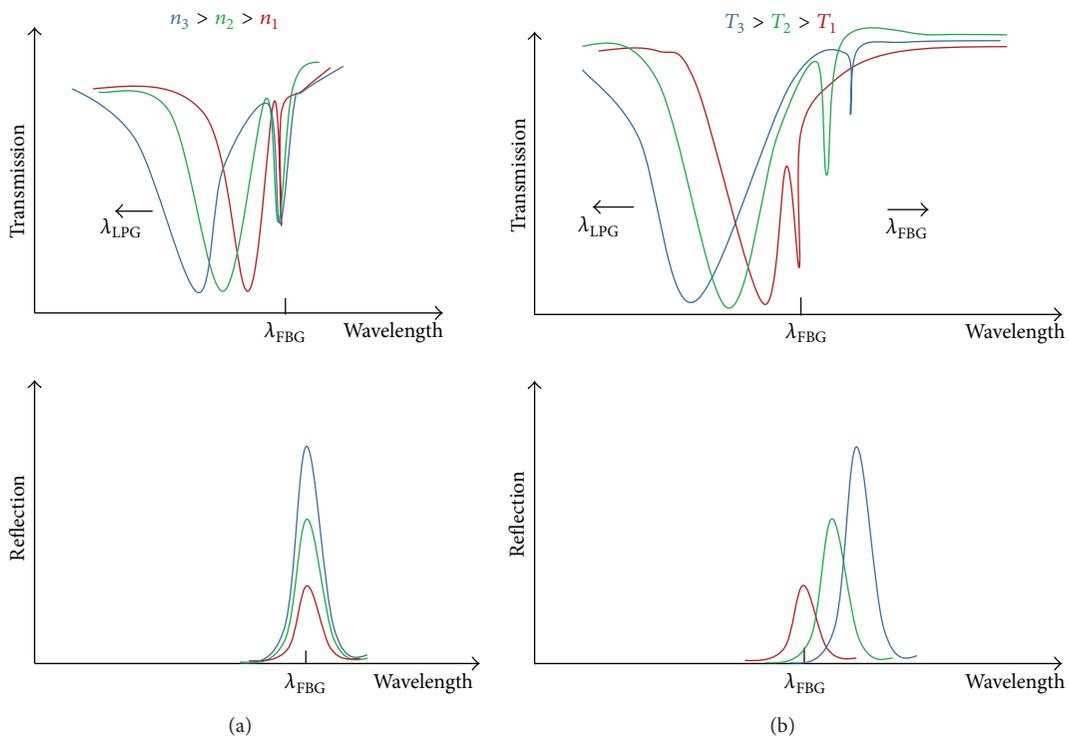


FIGURE 2: Schematic of the transmission and reflected spectrum of the hybrid sensor with refractive index (a) and temperature (b) changes.

3. Experimental Setup

3.1. Fabrication of the Gratings. The FBG is inscribed within photosensitive boron-germanium codoped optical fibre (Fibercore PS1250/1500) by irradiating it through a rectangular phase mask (1059.9 nm phase mask period) with an Excimer KrF Laser (LAMBDA PHYSIC COMPex 110). The characteristics of the fabricated FBG are as follows: ~ 1534 nm resonance wavelength and 1 cm length.

The LPG is written by a point-to-point technique within the same optical fibre, using the same laser. In this case the fibre is mounted on a motorized translation stage and is irradiated by the laser spot which is properly focused by means of a cylindrical lens and shaped through a micrometric

slit [8]. Both the translation stage and the laser action are controlled and synchronized by a PC, which makes it possible to choose both the grating period and the number of shots for each step. The grating period, the resonance wavelength, and the length of the fabricated LPG are $360 \mu\text{m}$, 1530.4 nm , and 1.8 cm , respectively.

Figure 3 shows the transmission spectrum of the fibre obtained at the end of the writing process of the two gratings. As it can be seen, the attenuation bands of both gratings occupy the same bandwidth, which is the key point of the proposed working principle as shown in Figure 1(b). Moreover, the position of the Bragg resonance very close to the LPG resonance peak ensures the widest possible T and RI operating ranges. The achievement of the FBG and LPG resonance

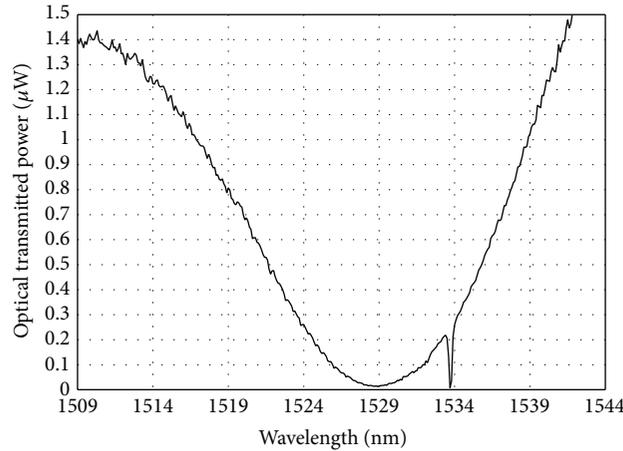


FIGURE 3: Transmission spectrum of the hybrid sensor at the end of the writing process.

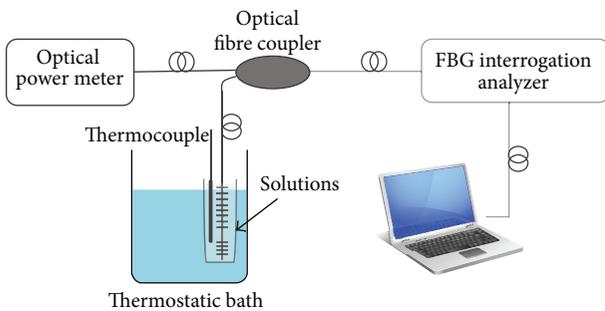


FIGURE 4: Experimental setup.

wavelengths centred at 1533.7 nm and 1530.4 nm, respectively, assures that this point is satisfied.

3.2. Interrogation System. In order to characterize the sensing performance of the cascaded LPG and FBG configuration, the surrounding refractive index (SRI) and thermal (T) sensitivities have been measured separately by analysing only the Bragg reflected spectrum. Figure 4 shows the experimental setup for this preliminary characterization. The sensing probe containing the gratings is placed into a thermostatic bath, whose temperature can be controlled by means of a thermocouple with a resolution of 0.1°C .

A Wave Capture FBG Interrogator System (with a wavelength range of 1510 nm–1590 nm and a resolution of 1 pm) is used for the detection of the Bragg reflected power and Bragg's resonance wavelength shift. Finally, an Optical Power Meter (ANDO AQ-2105 Optical Power Meter) is used in order to control and compensate any power fluctuations.

For the thermal characterization, the hybrid sensor is placed in a vial filled with pure water (refractive index 1.33) and placed into the thermostatic bath. The temperature of the thermal bath was heated from 14°C up to 63°C .

The response of the sensor in terms of resonance wavelength shift and Bragg reflected power was collected with the Bayspec-FBG Interrogator.

For the refractive index characterization, aqueous glycerine solutions at different concentrations with refractive index ranging from 1.33 to 1.47 with a step of 10^{-2} were used. The sensor was washed with distilled water after dipping in every aqueous glycerine solution. During the measurements the temperature was monitored and kept constant at 21°C .

4. Results and Discussion

As mentioned in the previous Section 2.1, the sensor response to temperature and refractive index changes can be obtained by monitoring only the Bragg reflection spectrum. When temperature increases, both the LPG and FBG resonance wavelengths shift to shorter and longer wavelengths, respectively, leading to a modification of the Bragg reflected spectrum in terms of reflected power modulation and resonance wavelength shift. In contrast, when surrounding refractive index changes, only the LPG resonance wavelength shifts, leading to an amplitude modulation of the Bragg reflected spectrum. Therefore, since the Bragg wavelength shift is induced only by temperature changes, it is possible to discriminate simultaneously the effects of temperature and refractive index.

The analysis of the thermal and RI response of the optical sensor was carried out with the experimental setup described in Section 3.2. Figure 5(a) shows the measured FBG wavelength shift as function of the temperature, when the water in the thermal bath was heated from 14°C to 63°C . As expected, the Bragg wavelength shift has a good linear behaviour with temperature variation, demonstrating a thermal sensitivity of $(8.65 \pm 0.07) \text{ pm } ^{\circ}\text{C}^{-1}$. Thus, based on the experimental results, (2) can be expressed as follows:

$$\Delta\lambda_{\text{FBG}}(T) = s_T \Delta T = (8.65 \pm 0.07) \text{ pm } ^{\circ}\text{C}^{-1} \Delta T. \quad (6)$$

Furthermore, the dependence of the FBG reflected power on temperature in water (1.33 RIU), reported in Figure 5(b), is linear in a range of temperature between 21°C and 46°C . Since the dependence of FBG's resonance wavelength and Bragg reflected power with temperature are both linear, it is possible to express directly the Bragg reflected power in terms

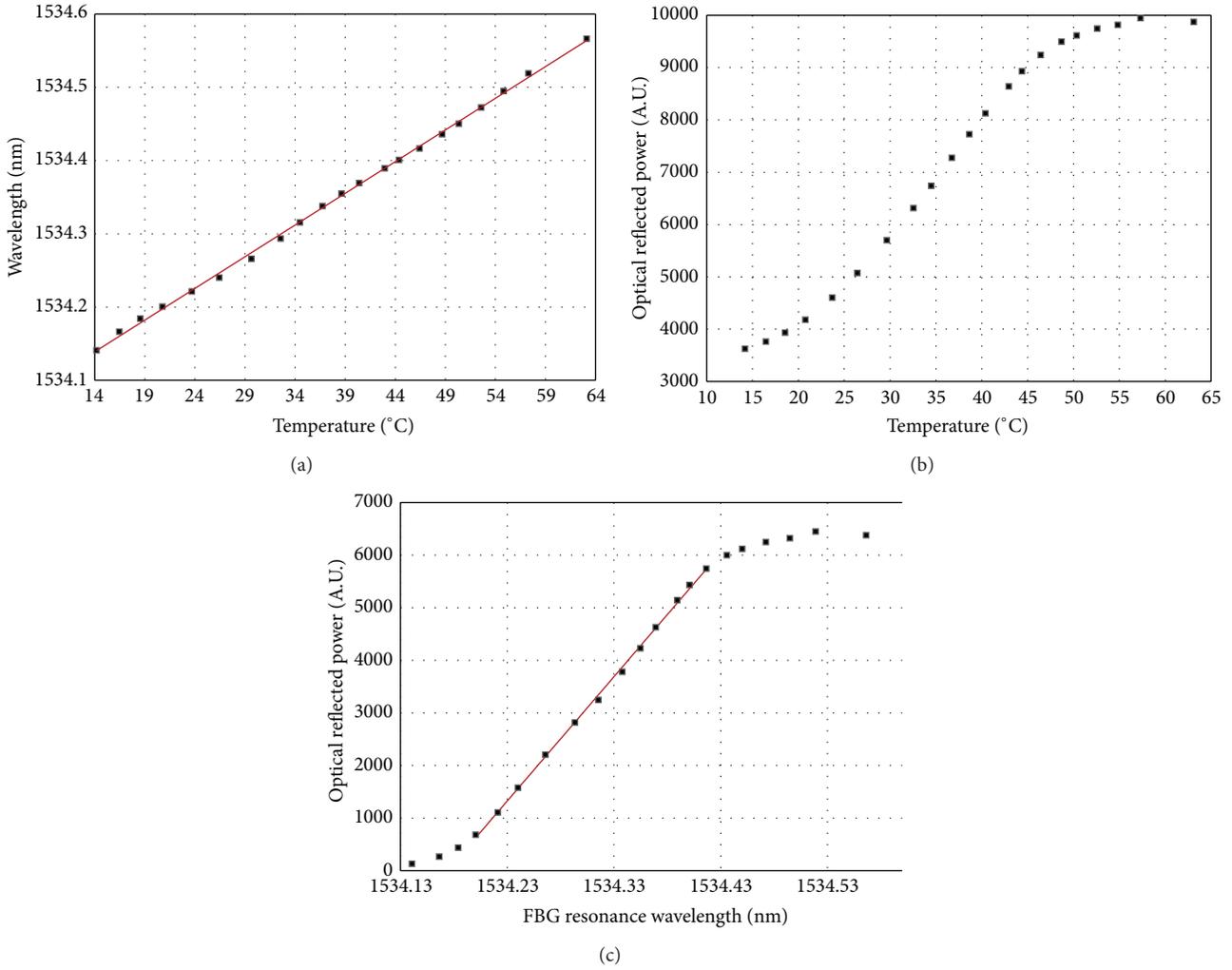


FIGURE 5: Thermal response of the hybrid sensor: (a) dependence of the FBG's wavelength shift on temperature; (b) relationship between Bragg reflected power and temperature; (c) relationship between Bragg reflected power and Bragg's resonance, temperature-induced, wavelength shift.

of Bragg's resonance, temperature-induced, wavelength shift, as previously described in Section 2.1. As it can be observed (Figure 5(c)), this relationship is linear in a wavelength range from 1534.2 nm to 1534.4 nm. Hence, within this temperature and wavelength ranges ($21^{\circ}\text{C} < T < 46^{\circ}\text{C}$ and $1534.2\text{ nm} < \text{RI} < 1534.4\text{ nm}$), the FBG's reflected power has a linear relationship with wavelength changes and can be expressed by the following equation:

$$\Delta P_{\text{FBG}}(T) = \gamma \Delta \lambda_{\text{FBG}} = (23640 \pm 240) \text{ A.U.} \cdot \text{nm}^{-1}, \quad (7)$$

where γ is the temperature sensitivity of the sensor provided by the slope of the fitting curve (red line) reported in Figure 5(c).

After the temperature characterisation, the sensor was characterised in terms of refractive index changes. The sensor was immersed in solutions with different RI prepared by mixing glycerol with deionized water in different ratios from 0% to 100%. The RI changes from 1.33 of pure water up to 1.47 of the last solution and the experiment was carried out

at a constant temperature (21°C) with the setup described in Section 3.2.

Figure 6 shows the measured Bragg reflected power changes due to solution's RI ranging from 1.33 to 1.47 at a temperature of 21°C .

As it can be observed, the Bragg reflected power has a nonlinear behaviour with an increase up to 1.43 and a steeper decrease for RI values greater than 1.43. In the range from 1.33 to 1.43, a good fitting of the experimental data is obtained by means of a rational curve expressed by the following equation:

$$P_{\text{FBG}}(n) = \frac{b + cn}{a + n} \quad (8)$$

with the coefficients a , b , and c providing the fitting parameters of the rational curve ($a = -1.55$, $b = -875$, and $c = 161$). The sensor maximum RI sensitivity is reached when the RI of the aqueous solution is very close to the cladding one.

In order to evaluate the working range of the hybrid sensor, a temperature characterization of the sensor for

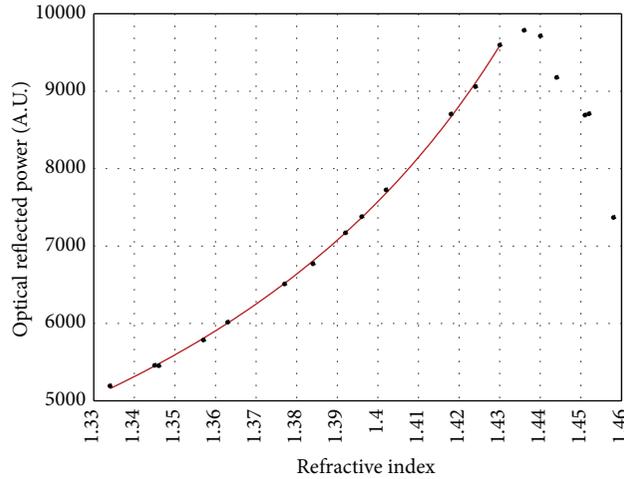


FIGURE 6: The relationship between Bragg reflected power and external refractive index at 21°C.

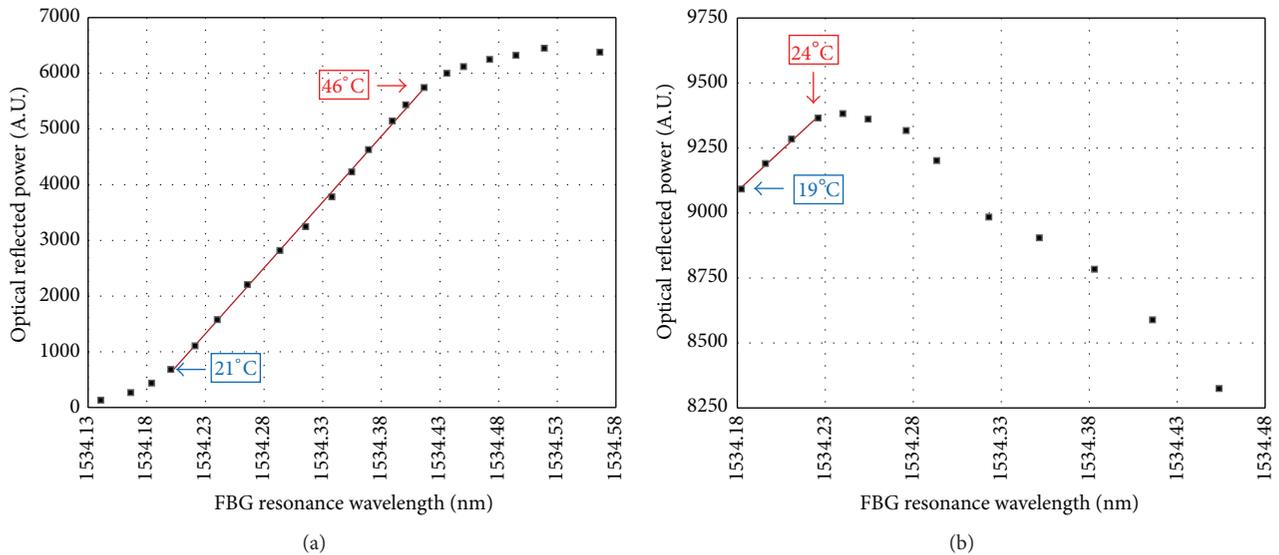


FIGURE 7: Temperature response at refractive index values 1.33 (pure water) and 1.43.

different values of refractive index in the range between 1.33 and 1.43 was carried out.

The measurement of the thermal response in pure water ($n = 1.33$) reveals a linear behaviour of the Bragg reflected power with respect to the resonance wavelength (Figure 7(a)) in a temperature range between 21°C and 46°C. Instead, when considering the solution with $n = 1.43$, the temperature range of linear response is smaller: from 19°C to 24°C (Figure 7(b)). This effect can be explained by observing both the qualitative description in Figure 2 and the transmission spectrum reported in Figure 3: as the RI of the solution increases, the LPG's resonance wavelength has a blue shift leading to an increase of the grating's resonance wavelength spectral distance. Thus, considering RI changes from 1.33 up to 1.43 the temperature range in which the relationship between the reflected power and the Bragg resonance wavelength is linear is very small: from 21°C up to 24°C. The reduction of the

thermal linear range is due to the LPG's resonance wavelength shift towards shorter wavelengths when the RI is increased.

In order to extend the temperature range of linearity, the analysis was performed considering solutions with refractive index ranging from 1.33 to 1.40. Thus, considering this RI range, the temperature interval of linear response is larger: from 21°C up to 28°C, as shown in Figure 8.

With reference to the solution with $n = 1.40$ the thermal sensitivity has the following expression:

$$\gamma = (23330 \pm 570) \text{ A.U} \cdot \text{nm}^{-1}. \quad (9)$$

From (5), the thermal compensated RI information can be achieved. The thermal coefficient γ is directly measured from the thermal response of the Bragg reflected power with respect to FBG's wavelength. Therefore, the RI response of the sensor is obtained by measuring the variation of the reflected

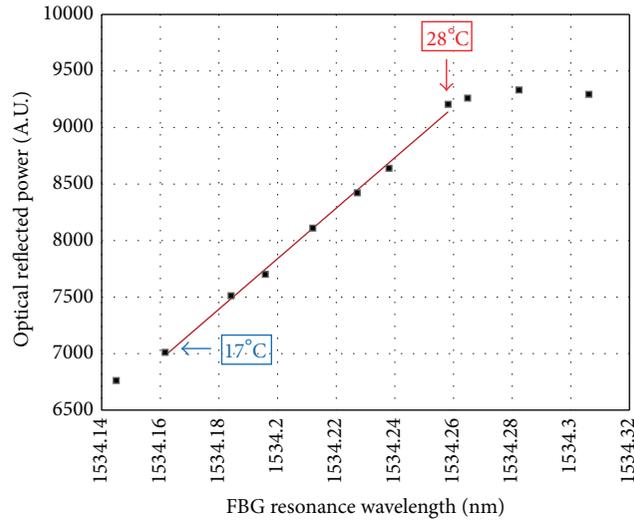


FIGURE 8: The temperature response at refractive index 1.40.

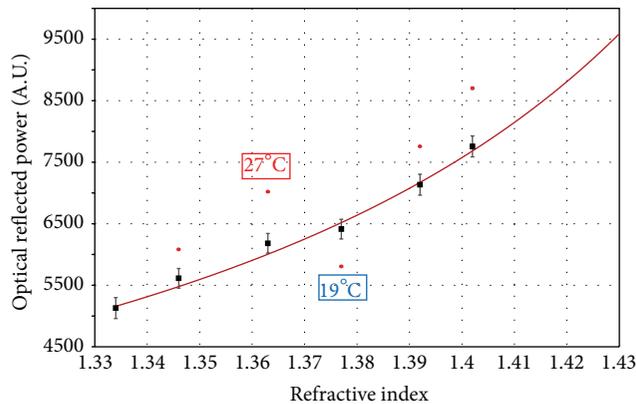


FIGURE 9: Temperature correction effect: Bragg reflected power before (red circles) and after (black square) the thermal compensation. The fitting curve describes the RI response of the sensor at 21°C (the same of Figure 6).

power and subtracting the contribution of the wavelength shift due to the temperature variation. Finally, by inverting the rational function expressed by (8), which describes the SRI response, the refractive index of the surrounding solution can be calculated.

In order to further demonstrate the correct operating principle of the proposed sensor for refractive index measurements with temperature compensation, a final test has been carried out. The sensor was immersed in solutions with different refractive index and in nonisothermal conditions, and both the Bragg resonance wavelength shift and the Bragg reflected power were measured with the Bayspec interrogator.

In Figure 9 the Bragg reflected power before (red circles) and after (black square) the thermal compensation, are reported. Using the compensation equation (4), the corrected points are distributed around the same fitting curve described previously (Figure 6), which describes the RI response of the sensor at 21°C. Hence the thermal effects are compensated. Considering all measurement error sources, the optical reflected power obtained from (4) is affected by a relative

error of about 2.5%. Moreover, since the sensitivity of the sensor is not constant in the 1.33–1.40 range, the maximum accuracy is achieved for high RI values.

The proposed solution allows measuring the RI of different solution by compensating the thermal effect in a temperature range from 21°C to 28°C and for RI ranging from 1.33 to 1.40 with an accuracy of about $4 \cdot 10^{-3}$.

If it is needed to change these intervals, as mentioned in Section 2, the design parameters of both gratings have to be redefined, in order to change their mutual position on the transmission spectrum.

5. Conclusions

In conclusion, a hybrid grating based sensor for simultaneous measurement of temperature and refractive index solutions is proposed and experimentally demonstrated. The T and the RI information can be deduced by monitoring only the Bragg reflected spectrum in terms of Bragg's wavelength shift and reflected power changes, and this provides a noticeable

simplification in the development of the interrogation system.

The LPG-FBG structure provides the RI measurement for values of the refractive index ranging from 1.33 up to 1.40 with a temperature compensation between 21°C and 28°C.

The maximum accuracy of the sensor is approximately $4 \cdot 10^{-3}$ RIU in the range 1.37 RIU–1.40 RIU. In terms of sensitivity and accuracy, the achieved sensor response is comparable with commercially available refractometers.

Thanks to the high chemical inertness of silica optical fibres, the proposed hybrid sensor can be safely applied in a wide variety of environments without risk of contamination of the surrounding medium and degradation of the sensor and, for these reasons, it is also suitable for very long term measurements (months or years).

Even if the dynamics in terms of temperature is not too much broad, the present sensor can be very useful for those applications where the temperature changes are limited to changes of the order of few degrees, as it occurs in laboratory measurements or in some industrial applications where the temperature is only roughly stabilised.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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