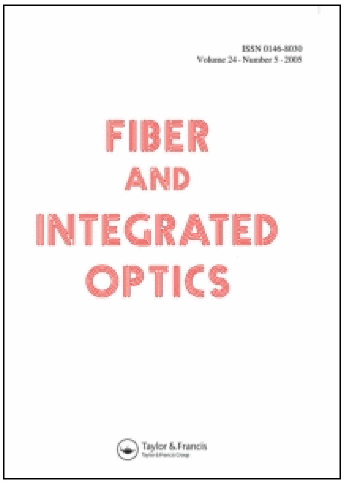

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C. Jesus [ab]; P. Caldas [ac]; O. Frazão [ad]; J. L. Santos [ad]; P. A. S. Jorge [a]; J. M. Baptista [ab]
[a] INESC Porto, Porto, Portugal [b] Department de Matemática e Engenharias, Universidade da Madeira, Funchal, Portugal [c] Escola Superior de Tecnologia e Gestão, Viana do Castelo, Portugal [d] Faculdade de Ciências da Universidade do Porto, Porto, Portugal

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Simultaneous Measurement of Refractive Index and Temperature Using a Hybrid Fiber Bragg Grating/Long-Period Fiber Grating Configuration

C. JESUS,[1,2] P. CALDAS,[1,3] O. FRAZÃO,[1,4] J. L. SANTOS,[1,4]
P. A. S. JORGE,[1] and J. M. BAPTISTA[1,2]

[1]INESC Porto, Porto, Portugal
[2]Department de Matemática e Engenharias, Universidade da Madeira, Funchal, Portugal
[3]Escola Superior de Tecnologia e Gestão, Viana do Castelo, Portugal
[4]Faculdade de Ciências da Universidade do Porto, Porto, Portugal

Abstract *A fiber optic sensing system for simultaneous measurement of refractive index and temperature, based on a hybrid fiber Bragg grating/long-period grating arrangement is described. The experimental results show that this setup has a good performance in terms of linearity and sensitivity, the ratiometric output changes 4%/0.001 RIU and 3.6%/°C, respectively. The sensor resolution for the refractive index is* $\approx 2 \times 10^{-5}$ *RIU. The simultaneous measurement of the refractive index and temperature was demonstrated. The sensing configuration has the ability to be read-out in reflection and works in the telecommunications window.*

Keywords fiber-optic sensors, gratings, refractive index, temperature, measurement

Introduction

It is currently recognized that the measurement and control of physical, chemical, and biological parameters in natural environments is of large importance for ecosystems monitoring and protection. In this context, the refractive index (RI) and temperature measurements in coastal and estuary environments are required as part of a process directed to the health assessment of their biodiversity. The RI has been used to measure the salinity of seawater, detect water pollutants, and monitor water quality. In particular, the level of salinity is not only a determinant for lagoon life species, but it is also an indicator of water conductivity—a parameter that is essential in the context of the utilization of electromagnetic techniques for the study of tidal dynamics by measurement of induced currents generated by huge masses of water in motion [1].

In this field, fiber-optic sensors offer important advantages such as high sensitivity, small size, and capability for on-site, real-time, remote, and distributed sensing. Optical fiber gratings, including fiber Bragg gratings (FBGs) and long-period fiber gratings (LPGs), are key elements in many optical telecommunication and sensing applications. They are characterized by a periodic index modulation of the RI of the core of a

Received 27 November 2008; accepted 26 August 2009.
Address correspondence to O. Frazão, INESC Porto, Rua do Campo Alegre, 687, Porto, 4169-007, Portugal. E-mail: ofrazao@inescporto.pt

single-mode fiber (SMF), where the LPG's period is much longer (hundreds of microns) than the FBG's period (typically a half-wavelength). This structural difference results in devices with fundamentally different properties and with a strong potential of application [2–4].

Several fiber gratings based sensors have been proposed. A simple Fabry–Pérot cavity with an FBG and fiber tip was demonstrated for RI measurement [5]. Another scheme, based on two FBGs, was used for simultaneous measurement of temperature and salinity, where one of the FBGs presents a smaller diameter of the cladding, allowing greater interaction of the evanescent field with the surrounding liquid [6]. Other FBG techniques based on the application of specific coatings have also been studied. For example, an FBG coated with a hydrogel has been demonstrated as a salinity sensor [7]; another system with two FBGs—one coated with a polyimide sensitive to the RI and another with a temperature sensitive acrylate polymer—was used for simultaneous measurement of temperature and salinity [8].

Other fiber-optic sensors for salinity that incorporate LPGs have been developed. For instance, a single LPG has been used as a sensitive refractometer [9]. A more advanced LPG-based interferometric configuration was also demonstrated [10]. Other examples include a system with two LPGs, where one is etched, enabling the simultaneous measurement of temperature and salinity [11]. Moreover, the coating of LPGs with thin films to increase sensitivity to environmental parameters has also been the subject of study [12]. Other types of refractometric fiber-optic sensors that have been used for the measurement of salinity, such as surface plasmon resonance (SPR) techniques, offer very high sensitivity [13, 14]. Nevertheless, these configurations are read-out in transmission or require etching processes that introduce fragility in the fiber sensor.

In this article, an alternative configuration is demonstrated for simultaneous measurement of the RI (n) and temperature based on a hybrid system with one LPG for RI sensing and two FBGs for dynamic interrogation system and temperature compensation.

Experimental

The hybrid FBG/LPG sensor and detection system are shown in Figure 1. This setup was used for simultaneous measurement of temperature and strain [15]. The sensing head consists of three gratings, one LPG with period $\Lambda = 395\ \mu$m (written by the electric-arc technique) and center wavelength $\lambda_{LPG} = 1{,}545$ nm, and two FBGs (written by the UV-phase mask technique) with center wavelengths $\lambda_{FBG1} = 1{,}540$ nm and $\lambda_{FBG2} = 1{,}550$ nm, respectively. The gratings are arranged as depicted in Figure 1; the first grating is the LPG, and next are the two FBGs, where the relative spectral position of each grating was chosen in order to have one reflection peak on each side of the LPG resonance. The relative distances of all the gratings, much larger than the coherence length of the optical source, and their relative spectral positions eliminate the possibility of any interferometric induced noise. The inset in Figure 1 also shows the relative spectral position of the gratings and their behavior for two different refractive indices.

With the proposed configuration, the resonant peak of the LPG shifts in wavelength in accordance with the variations of the n of the surrounding medium. This perturbation thus changes the intensity of light reflected by the two FBGs. The n measurement can be obtained in reflection by a simple calculation of the ratio between the intensities reflected by the two FBGs. This ratio is proportional to the wavelength shift, and thus to the external RI, but is independent of any other optical power fluctuations. Temperature, on the other hand, can be obtained by monitoring the shifts of the center wavelength of either one

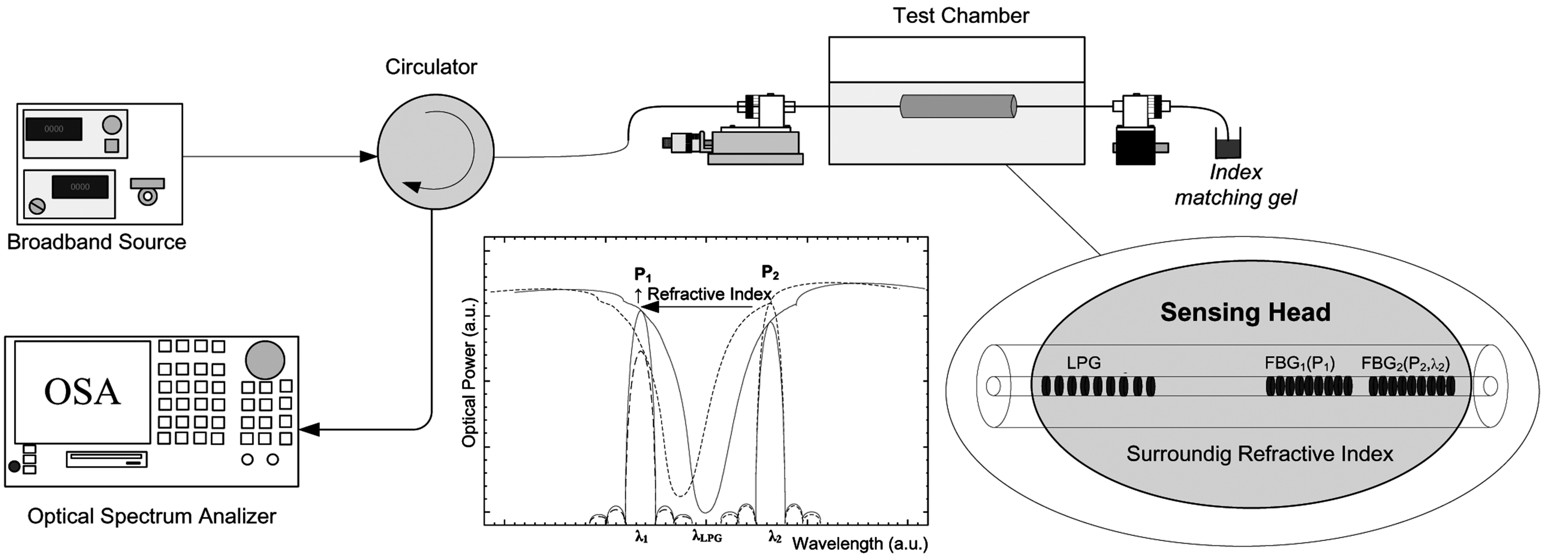


Figure 1. Sensing head and experimental results.

of the FBGs. The temperature and RI response of the LPGs were previously measured and were approximately 98 pm/°C and 95 pm/0.001 RIU, respectively. The sensing scheme shown in Figure 1 was implemented to test and characterize the hybrid configuration. An erbium-doped fiber broadband source that emits in the 1,550-nm range was used. The power spectrum was measured with an optical spectrum analyzer (maximum resolution of 10 pm). In the distal end of the sensing head, index matching gel was used in order to avoid Fresnel reflection. For calibration, the sensing head was immersed in samples of water mixed with different percentages of ethylene glycol at a constant temperature (20°C) to provide for the RI standards. The liquid samples were previously characterized by an Abbe refractometer using the sodium D line (589 nm). Due to dispersion, the actual RI of the solutions at 1,550 nm should be different. Nevertheless, in a previous work, it was verified that although the absolute values of the RI are indeed distinct, the small incremental RI change Δn of the different solutions remain relatively constant as a function wavelength. Therefore, the values obtained with the sodium line actually provide a reasonable estimate of the system sensitivity [6].

Results and Discussion

Figure 2a presents the modulation of the optical power reflected by FBG1, which was caused by the shift of the LPG resonance as a consequence of the changes in the n of the surrounding medium. As the RI increases, the LPG resonance starts to overlap the FBG1 resonance, and the power reflected by FBG1 is attenuated. As expected, the central wavelength of the FBG spectrum is independent of the RI changes. Figure 2b illustrates the spectrum behavior of the FBG2 spectrum when the sensing head is subjected to an increase of temperature. In this case, not only do the wavelengths shift toward longer wavelengths, but they are also attenuated due to the interaction with the LPG resonance.

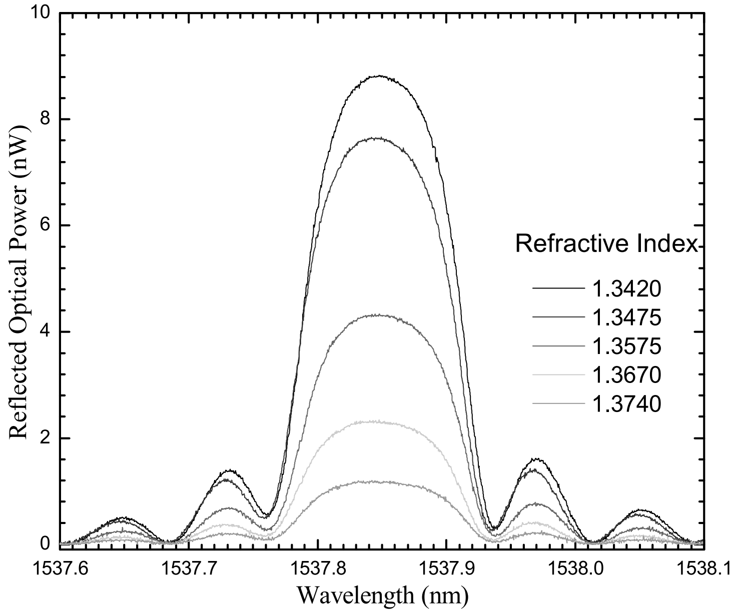
In order to analyze the RI variation, a normalized power ratio of the two FBGs was defined ($R = I_1 - I_2/I_1 + I_2$), where I_1 and I_2 are the reflected intensities of FBG1 and FBG2, respectively. In Figure 3, the responses of the R parameter as a function of the RI variation is shown together with the measurement of the center wavelength of FBG2. A linear variation of the R parameter against the n variation (4%/0.001 RIU) is observable. On the other hand, the wavelength shift of FBG2 is negligible and is probably due to minute temperature fluctuations.

To obtain the resolution in the measurement of the RI, the sensing head was subjected to a step change of n (Figure 4). From this approach, an RI resolution of $\approx 2 \times 10^{-5}$ was obtained by considering a minimum detectable signal of two times the standard deviation.

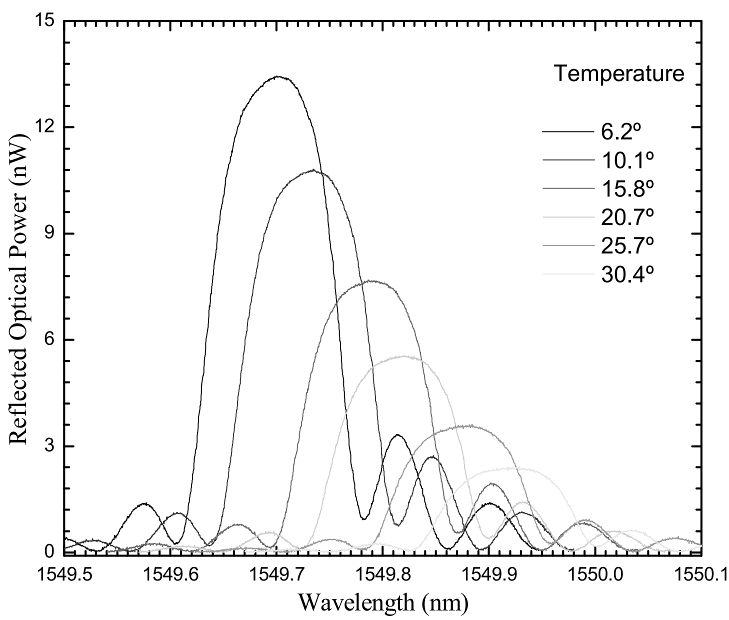
For temperature characterization, the sensing head was immersed in distilled water. Figure 5 shows the optical spectra of FBG2 in response to temperature changes in the range of 5°C to 31°C, where a variation of 9.30 pm/°C was observable. The expected variation of the RI with temperature is very low and approximately 0.2×10^{-5}/°C [16]. Nevertheless, due to the wavelength shifts of both the FBGs and the LPG, the R parameter is affected by temperature (3.6%/°C). The responses of the R parameter and of the $\Delta\lambda_{FBG2}$ to temperature variations are shown in Figure 5.

The dual response of the FBGs power ratio (R parameter) and the FBG2 wavelength allows for the writing of a conditioned system of two equations for Δn and ΔT, given in matrix form as

$$\begin{bmatrix} \Delta T \\ \Delta n \end{bmatrix} = \frac{1}{-K_{nR} K_{T\lambda}} \begin{bmatrix} 0 & -K_{nR} \\ -K_{T\lambda} & K_{TR} \end{bmatrix} \begin{bmatrix} R \\ \Delta\lambda \end{bmatrix},$$



(a)



(b)

Figure 2. (a) Modulation of the reflected FBG1 optical power caused by the shift of the LPG wavelength in response to the surrounding RI. (b) FBG2 optical spectra in response to temperature changes.

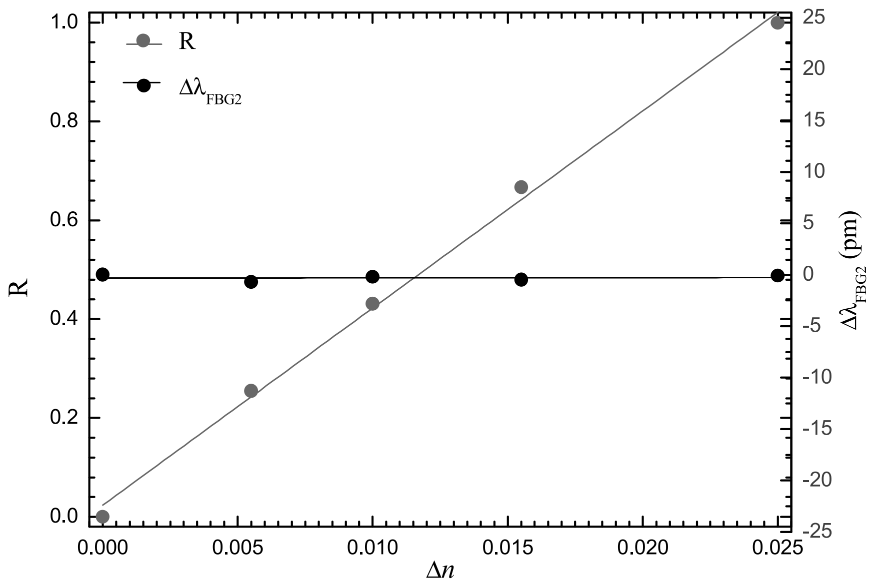


Figure 3. *R* parameter and FBG2 wavelength shift responses with RI variation.

where K_{nR} and $K_{T\lambda}$, the matrix coefficients, are the slopes of the lines represented in Figures 3 and 5, respectively [17].

$$\begin{bmatrix} \Delta T \\ \Delta n \end{bmatrix} = \frac{1}{-0.37} \begin{bmatrix} 0 & -39.87 \\ -0.0093 & 0.2 \times 10^{-5} \end{bmatrix} \begin{bmatrix} R \\ \Delta\lambda \end{bmatrix};$$

from the *R* parameter and the FBG2 wavelength responses, this equation allows recovering the RI and the temperature without ambiguity. To test this concept, simultaneous

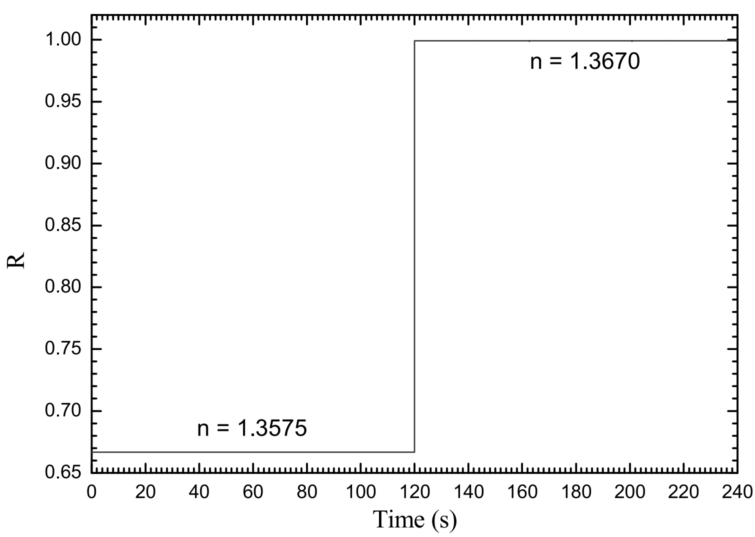


Figure 4. RI resolution.

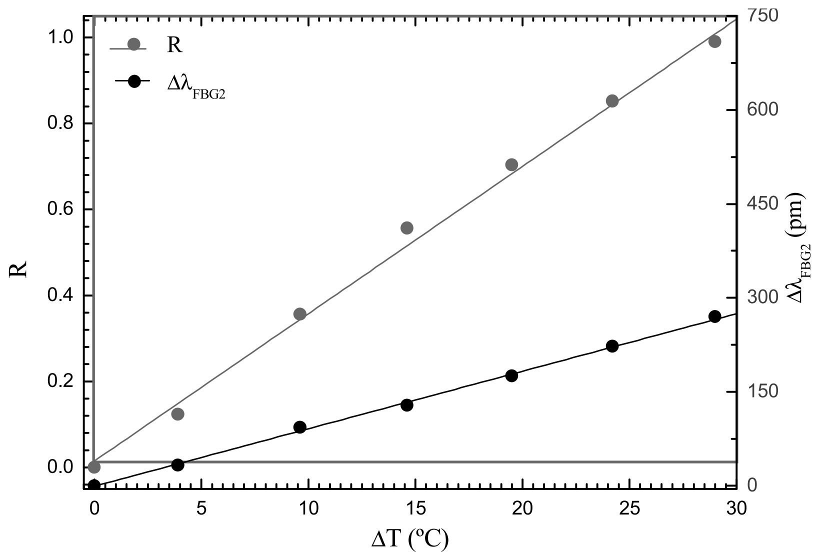


Figure 5. *R* parameter and FBG2 wavelength shift responses with temperature variation.

changes in temperature and RI were induced in the sensing head. Figure 6 presents the results of the simultaneous measurement of the temperature and RI using the matrix method. For the RI, the results were also compared with the measured ones by the Abbe refractometer. As it can be seen, they are in good agreement.

In this study, the possibility of absorptive external media was not addressed. However, in a practical application, the imaginary part of the RI can be a concern, and a detailed study should be performed. Nevertheless, the use of the ratiometric scheme can provide some immunity for absorption as long as both the FBGs are attenuated in the same way. For fluids with more complex absorption spectra, a careful choice of the gratings and the use of protective/filtrating membranes should be investigated.

Conclusion

A compact sensing head based on the LPG/FBG hybrid system has been described. Its capability of the simultaneous measurement of the RI and temperature has also been demonstrated. The sensing configuration exhibited *n* linear response with sensibility of 4%/0.001 RIU and resolution of 2×10^{-5}. The sensing configuration has the ability to be read-out in reflection. Therefore, measurements can be performed using standard FBG interrogation units while having the advantage of the evanescent sensitivity of LPGs. Therefore, it has good characteristics for application in salinity measurements or for detection of pollutants and other chemical substance, provided the sensitive region is coated with adequate chemically sensitive membranes.

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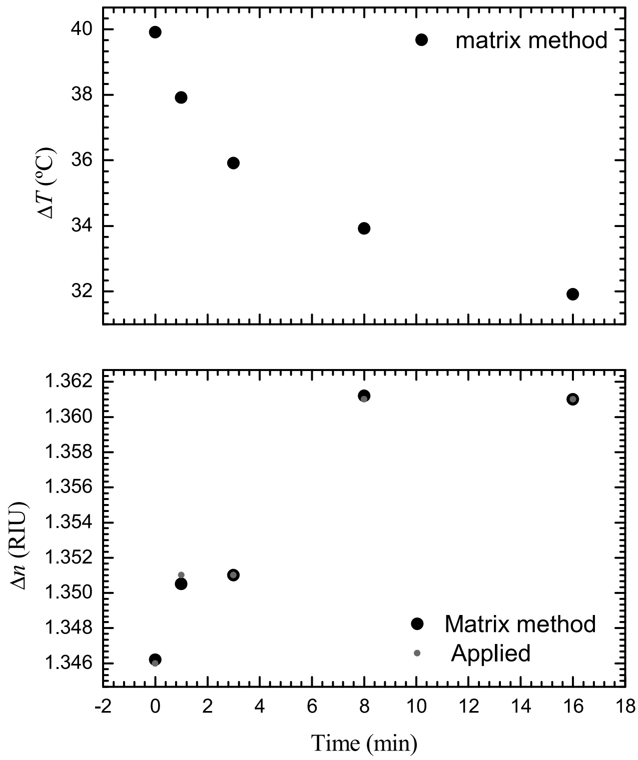

Figure 6. Simultaneous measurement of temperature and RI.

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Biographies

Carlos Jesus was born in Venezuela. He received his master's degree in engenharia de telecomunicações e redes at the University of Madeira. From March 2008 to September 2008, he made his internship at the the INESC Porto Optoelectronics and Electronics Systems Unit, where he studied biosensors using fiber optics.

P. Caldas graduated in applied physics (optics and lasers) from the University of Minho in 1999. He received the M.Sc. degree in lasers and optoelectronics in the physics department of the University of Porto in 2003. He is currently a researcher in the Optoelectronics and Electronic Systems Unit at INESC Porto, is working toward his Ph.D. in optical fiber sensors based in evanescent field interaction at the physics department of the University of Porto, and is teaching physics at the Polythenic Institute of Viana do Castelo. He has published approximately 20 journal and conference papers and holds one patent.

O. Frazão graduated in physics engineering (optoelectronics and electronics) from the University of Aveiro, Portugal. He is currently working towards his Ph.D. degree in physics at the University of Porto, Porto, Portugal. From 1997 to 1998, he was with the Institute of Telecommunications, Aveiro. Presently, he is a researcher at Optoelectronics and Electronic Systems Unit, INESC Porto. He has published approximately 275 papers, mainly in international journals and conference proceedings, and his present research interests include optical fiber sensors and optical communications. He is a member of the Optical Society of America (OSA) and European Physics Society (EPS).

J. L. Santos graduated in applied physics (optics and electronics) and received his Ph.D. degree in physics from the University of Porto, Porto, Portugal, for research in fiber-optic sensing, in 1983 and 1993, respectively. He is an associate professor of physics at the University of Porto and is in charge of the Optoelectronics and Electronic Systems Unit, INESC Porto. His main research interests are in the optical fiber sensing field. He is a member of the Optical Society of America (OSA) and the International Society for Optical Engineers (SPIE).

Pedro Alberto da Silva Jorge graduated in applied physics (optics and lasers) from the University of Minho in 1996. He received his M.Sc. in optoelectronics and lasers from the physics department of the Univerisity of Porto in 2000 with his dissertation on optical current sensors for high voltage operation. In 2006, he concluded his Ph.D. program at Porto University in collaboration with the department of physics and optical sciences at the University of Charlotte, North Carolina, USA, with work developed in luminescence based optical fiber systems for biochemical sensing applications. The work involved studies of the applicability of luminescent nanoparticles as tools for biochemical sensing. He is currently a senior researcher at INESC Porto, where he leads a small team that is aiming to explore the potential of optical fiber and integrated optic technologies in the development of biochemical sensors for environmental and medical applications. He has published approximately 20 journal and conference papers and holds one patent.

J. M. Baptista graduated in electrical and computer engineering from the University of Porto, Porto, Portugal, in 1991. He received his M.Sc. degree in physics of laser communications from the University of Essex, Colchester, UK, in 1992, and the Ph.D. degree in electrical and computer engineering from the University of Porto in 2002. Currently, he is an assistant professor of the mathematics and engineering department at the University of Madeira and is a researcher at the Optoelectronics and Electronics Systems Unit, INESC Porto. His research interests are in the areas of fiber-optic sensors and optical communications. He is a member of the Institute of Electrical and Electronics Engineers (IEEE).