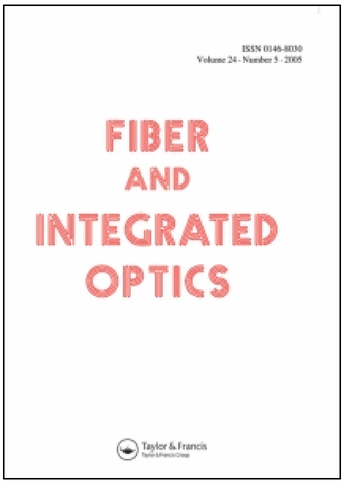

Fiber and Integrated Optics
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713771194

Optical Fiber Sensing System Based on Long-Period Gratings for Remote Refractive Index Measurement in Aqueous Environments

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Online publication date: 14 May 2010

To cite this Article Silva, C. , Coelho, João M. P. , Caldas, P. , Frazão, O. , Jorge, P. A. S. andSantos, J. L.(2010) 'Optical Fiber Sensing System Based on Long-Period Gratings for Remote Refractive Index Measurement in Aqueous Environments', Fiber and Integrated Optics, 29: 3, 160 — 169

To link to this Article: DOI: 10.1080/01468031003759493

URL: http://dx.doi.org/10.1080/01468031003759493

Fiber and Integrated Optics, 29:160–169, 2010

ISSN: 0146-8030 print/1096-4681 online
DOI: 10.1080/01468031003759493

Optical Fiber Sensing System Based on Long-Period Gratings for Remote Refractive Index Measurement in Aqueous Environments

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Abstract *In the field of aqueous environment studies, long-period fiber gratings are very attractive for the real-time monitoring of physical parameters, such as temperature and salinity. However, due to the fiber jacket removal, these are fragile devices when applied in real conditions, where mechanical loads and contamination with algae and other organic materials must be taken into account. This work describes a refractive index sensing head that has been developed and characterized for in situ measurement of water salinity and resistance to hard conditions.*

Keywords fiber-optic sensors, long-period gratings, refractive index measurement

1. Introduction

Environmental monitoring is a factor of greater importance in the preservation of different species existing in estuaries and coastal environments. Gradient temperature and salinity are limiting factors of their development, so the knowledge and control of these parameters is critical for the ecosystem's health. In this context, several technologies have been developed in order to measure and monitor these environmental parameters [1–3]. Accurate measures of salinity are based on the mobility of ions in water [4]. However, these methods are inherently electrical and can be affected by any kind of electromagnetic interference [4]. Optical-fiber refractometers (OFRs) are an alternative to conventional methods for use in natural environments to monitor different parameters. OFRs have many advantages, such as immunity to electromagnetic interference, small size, non-intrusive nature, flexible geometry, high response speed, and excellent salt water

Received 7 January 2010; accepted 18 February 2010.
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corrosion resistance [5]. They can also be multiplexed in large numbers along a single optical-fiber transmission cable to facilitate in situ distributed sensor networks.

Because of these favorable characteristics, the interest in developing fiber-optic salinity sensors has increased in the past few years. Some of them, based on refractive index measurements, have recently been presented [6, 7]. In particular, long-period fiber gratings (LPGs) have attracted a lot of attention because of their high sensitivity to the refractive index of the surrounding environment [8, 9].

An LPG is a fiber structure associated with a periodic core refractive index modulation [5]. The large modulation period promotes optical coupling between the fundamental core mode and specific cladding modes, causing rejection bands in the transmission spectrum. The environment surrounding the fiber at the grating location can influence the transmission spectrum, because external perturbations can cause corresponding changes in the grating length, periodicity, or differential effective refractive index of the fiber. Such changes in LPG parameters cause corresponding shifts in the coupling wavelength and change the depth of loss bands. Measurement of the loss band wavelength shift in response to a change in these parameters is the basis of sensing with LPGs [8, 10, 11].

This grating device has the advantages of low back-reflection and insertion loss, insensitivity to electromagnetic interference, easy manufacturing, and cost effectiveness. Its large sensitivity to the refractive index variations of the environment where it is immersed arises from the dependence of the effective index of the cladding mode on the refractive index of the surrounding environment. The sensitivity to the refractive index changes increase with the reduction of that difference.

Several authors have experimentally demonstrated different configurations for the application of LPGs as refractometric sensors [12–15]. However, due to the fragile nature of these structures, the present technical status of LPG refractometric sensors when applied in real conditions is not satisfactory. In this context, the study of a system that enables the use of the favorable intrinsic characteristics of LPGs for in situ measurement of the refractive index of the external medium and, from this, its salinity level, is relevant. Thus, in this work, the prototype of an LPG-based refractometric sensing system for demanding field applications is presented, and its influence in the sensor performance evaluated.

2. Theoretical Background

An LPG consists of a periodic modulation of the refractive index of the core of an optical fiber with periodicity in the range of 100–1,000 μm. The characteristics of this structure can be described using the coupled-mode theory in the context of coupling the core mode to the discrete cladding modes. This coupling appears in the transmission spectrum as discrete loss bands, which are centered at wavelengths that satisfy the following phase matching condition [16, 17]:

$$\beta_{core} - \beta_{clad}^{m} = 2\pi/\Lambda, \tag{1}$$

where β_{core} and β_{clad}^{m} are the propagation constants of the fundamental core mode and the mth cladding mode, respectively; Λ is the grating period; and m is the order of the cladding mode. Based on Eq. (1), the resonant wavelength associated with the mth cladding mode is

$$\lambda_{res}^{m} = [n_{eff,co}(\lambda) - n_{eff,cl}(\lambda)^{m}]\Lambda, \tag{2}$$

where $n_{eff,co}(\lambda)$ and $\mathrm{n}_{eff,cl}(\lambda)^{m}$ are the effective refractive indices of the core and mth cladding modes, respectively.

The presence of an external perturbation affects the coupling strength between the core and cladding modes, which could cause the resonant wavelength to shift. This spectral shift is distinct for each loss band and is a function of the order m of the corresponding cladding mode.

The temperature sensitivity of the coupling wavelengths arises from the difference between the thermo-optic coefficients associated with the cladding and core modes. The following differential equation of the phase matching can be used to describe the temperature (T) dependence of the resonant wavelength:

$$d\lambda res^m/dT = \Lambda X[d(n_{eff,co}(\lambda) - n_{eff,cl}(\lambda)^m)/dT] + (n_{eff,co}(\lambda) - n_{eff,cl}(\lambda)^m)X(d\Lambda/dT). \quad (3)$$

As mentioned before, an interesting attribute of LPGs is their sensitivity to changes in the refractive index of the surrounding medium. This feature comes from the dependence of the resonance condition on the effective refractive index of the cladding mode associated with that resonance. This refractive index also depends on the refractive index of the fiber surroundings n_{sur}, due to the modal evanescent field interaction in the cladding–surrounding environment interface. The influence on the resonant wavelength of variations in the refractive index of the medium surrounding the cladding of an LPG is expressed by

$$d\lambda res/dn_{sur} = d\lambda/dn^m_{eff} + dn^m_{eff,cl}/dn_{sur}. \quad (4)$$

3. Experimental Arrangement

The harsh environment where the LPGs are to be deployed, combined with the optical fiber fragility, leads inevitably to the development of adequate encapsulation schemes. The system proposed in this work, illustrated in Figure 1, allows proper housing of the sensing element and optical fiber connectivity. In the conceptual design of this structure, a number of important technical issues were considered to apply this technology to the measurement of physical parameters. For example, in order to make accurate measurements, the sensing region (i.e., the LPG) must be firmly attached to the support, which, in this case, is the metallic housing surrounding the grating. The device allows controlling the tension in the optical fiber by means of a spring. This was projected to keep the grating under a constant longitudinal stress during the measurements. This fact helps to reduce potential cross-sensitivity problems. The grating is surrounded by enough space to promote the flow of running water enabling the accurate measurement of its refractive index and, consequently, of its salinity. Also, considering the problem of temperature cross-sensitivity, the system was designed to include a fiber Bragg grating (FBG) for measurement of this parameter.

The filtration of organic materials, which can be deposited over the LPG, thus changing the resulting signal, is obtained through membrane separation processes. The main limitation of this process is the blocking of the flux that occurs when the particles are deposited into the membrane, decreasing its filtering capacity. Several membranes were tested in order to characterize their performance under working conditions. One other crucial aspect to take into account is the easiness of cleaning of the device. This was accomplished by assuring that filters are replaced without interfering with the sensing process.

An erbium-doped broadband light source (Fiber White, EDFA FIBERAMP-BT 1400, Photonetics, France), with an emission centered on 1,550 nm, illuminates the sensing

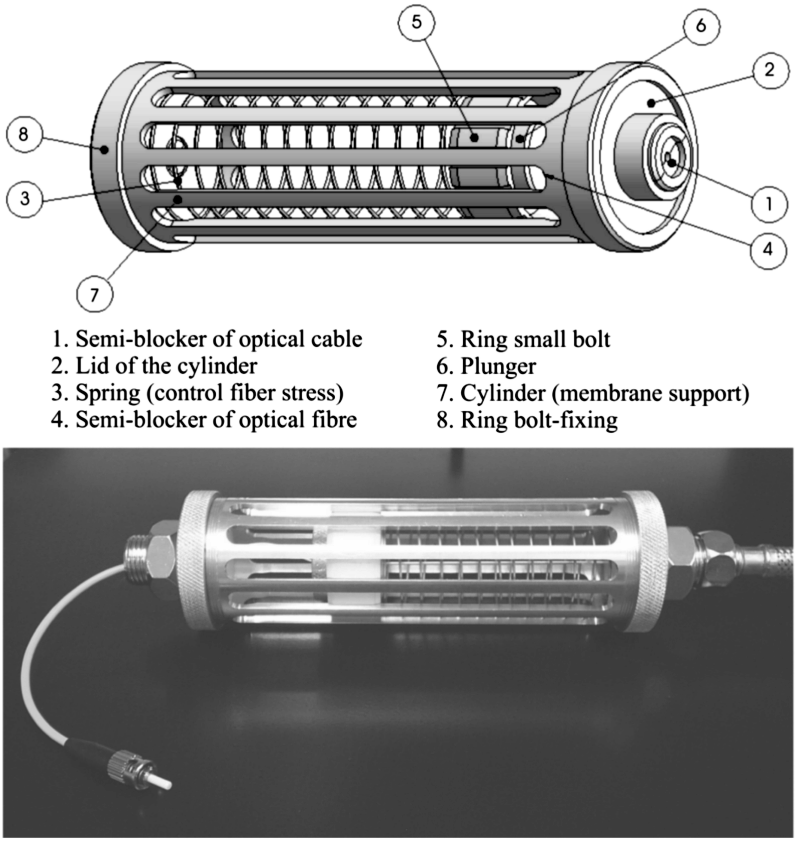


Figure 1. Schematic configuration and photo of the developed prototype for in situ measurement.

element. From the transmitted broadband spectrum, the refractive index can be measured from the spectral shift of the LPG attenuation band. This shift was monitored using an optical-spectrum analyzer (ANDO AQ-6330, ANDO Corporation, Japan). A preliminary performance evaluation of the sensing system was done in laboratorial conditions.

3.1. Refractive Index Measurement

To check the performance of the system developed for refractive index measurement, the sensitivity of the LPG-based sensing head to the refractive index change of the external medium was characterized. For calibration purposes, the LPG was immersed in liquids with different refractive indexes at room temperature in both situations, i.e., standing free and integrated into the projected structure. A mixture of water and different ethylene glycol concentrations were used, resulting in samples with refractive indexes in the range of [1.33, 1.43]. All readings were taken 1 min after the LPG was immersed in the solution. During the measurements, the fiber was maintained straight, and the tension was held constant.

The LPG studied in this work was written by electric arc discharge in a standard telecommunication fiber (SMF-28, Corning, Glendale, Arizona, USA) with a period of $\sim$540 μm and a length of $\approx$2 cm. It was considered that the rejection band was near the

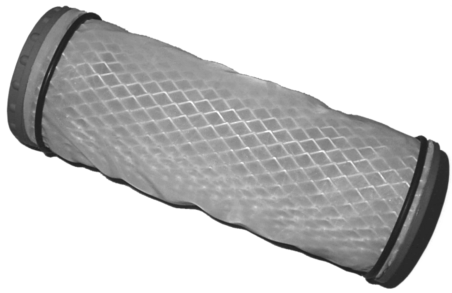


Figure 2. Membrane mounted on its support for testing.

wavelength of 1,500 nm (fourth-order coupling band). To further enhance its sensitivity for refractive index changes, the fiber diameter was reduced. This was made by chemical attack with an aqueous solution of hydrofluoric acid (HF 40%).

3.2. *Salinity Measurement*

In order to analyze the influence of the salt concentration, the spectral responses of the LPG mounted in the structure was measured when it was immersed in water with different salt concentrations, resulting in salinity levels between 1% and 19%.

3.3. *Temperature Measurement*

To study the influence of the temperature on the developed structure, the system performance was checked when the temperature changed in steps of 5°C between 0°C and 75°C in the air.

3.4. *Membranes Testing*

Three types of membranes were tested in real conditions in order to assess their filtering performance: a 2.7-μm pore size glass membrane and 53-μm and 100-μm pore size nylon membranes. Tests were made independently of the projected prototype and consisted of fixing the membranes to cylindrical supports (Figure 2), allowing the exposure of the membranes to the conditions of Ria de Aveiro, a Portuguese estuarine ecosystem, where they stayed for a period of one month. The degree of saturation of the filter was analyzed by optical microscopy.

4. Results and Discussion

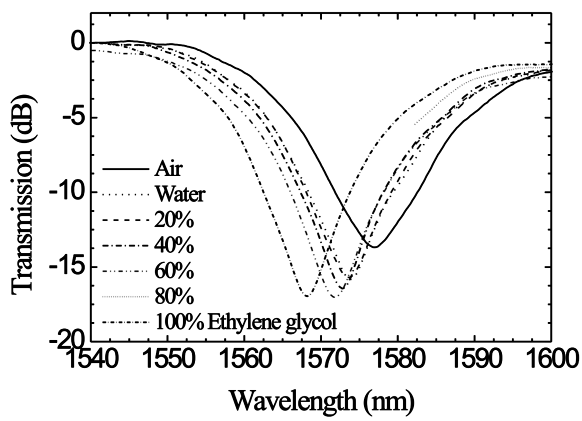
Concerning the membrane's behavior in real conditions, its analysis was performed in order to select the best filter for the application. After being submersed for the period mentioned before, it was found that the glass fiber filters disappeared, indicating that this type of filter does not tolerate this kind of environment. Also, based on optical microscopy, from the two nylon membranes, the one that has demonstrated a better performance (i.e., lower saturation after one month) was the one with the 53-μm pore size. Even so, the obtained results show that the membrane should be replaced with a periodicity of two or three weeks.

Focusing now on the intrinsic characteristics of the sensing head, Figure 3 shows the grating responses (fourth-order resonance band) to the surrounding medium solutions with increasing concentration of ethylene glycol, with the device either free (without curvature) or integrated in the structure. The initial spectrum of the LPG in air is also shown for reference.

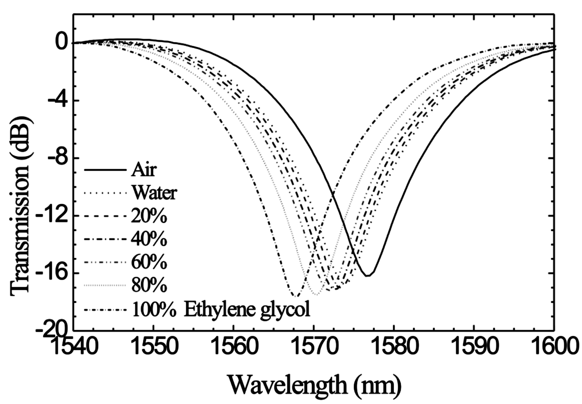
It can be seen that the resonance wavelength moves toward the shorter wavelength region as the concentration of ethylene glycol is increased. This can be understood through an increase of the effective refractive index of the cladding, which, according to the resonance condition, leads to lower resonant wavelengths [18, 19].

The relationship between the refractive index and the central wavelength shift of the fourth-order coupling band of the LPG is shown in Figure 4. The shift is with reference to the spectral position, with air as the surrounding medium.

It can be seen that for both situations, there is a similar response of the grating to refractive index changes. The slope of the calibration curves obtained gives an idea about the sensitivity of the refractometer. For a refractive index around 1.40, the sensitivity of the LPG is ≈ -67 nm/RIU and -57 nm/RIU for the cases where the device is mounted and free, respectively (RIU: refractive index unit). This difference is an indication that the



(a)



(b)

Figure 3. Evolution of the transmission spectra of the LPG as the refractive index is changed by increasing the concentration of ethylene glycol: (a) free and (b) mounted in the structure.

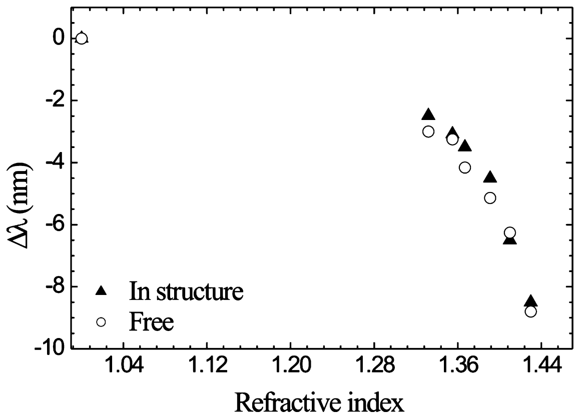


Figure 4. Resonance wavelength shift of the LPG measured for different refractive indexes of the external medium in the situations where the device is free (white circles) and integrated in the structure (black triangles).

pre-strain of the LPG in the structure induces a small enhancement of its refractive index sensitivity. As expected, it was also observed that the sensitivity increases substantially when the refractive index of the external medium is close to the cladding refractive index [9, 12].

The spectral response evolution of the LPG when mounted in the structure for different salinity levels was studied. This evolution is shown in Figure 5 for salt water solutions with different weight concentrations ranging from 0% to 19%. It can be observed that the resonance wavelength moves toward the shorter wavelength region (shift of $\approx$2 nm for the salt concentration range tested). This is due to the fact that, with an increasing concentration of salt, there is an increase in the refractive index of the solution. Also, it turns out that the solution salt concentration does not substantially affect the amplitude of the LPG loss band (variation less than 0.07 dB). The inset box of the figure

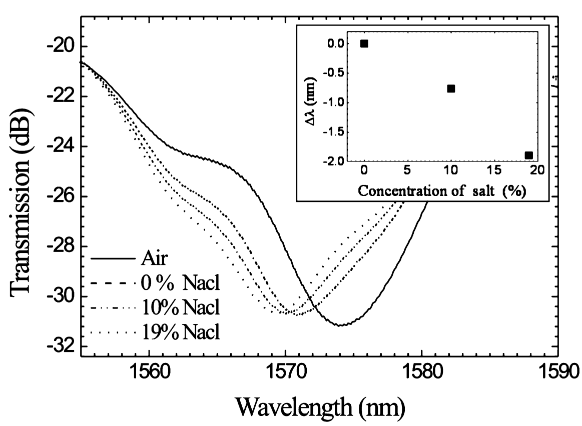


Figure 5. Transmission spectra of the integrated LPG sensing head in an aqueous solution containing increasing concentrations of salt (the inset graph shows the variation of the loss band central wavelength with the salt concentration).

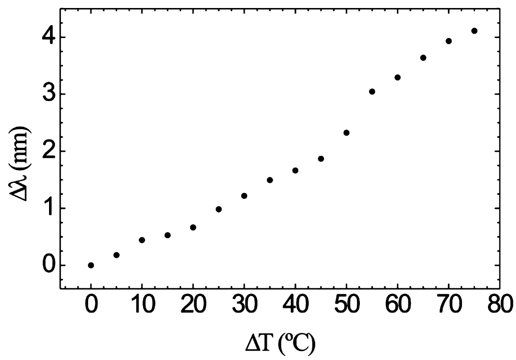


Figure 6. Variation of the LPG resonance with temperature for the integrated sensing head.

shows the resonance wavelength shift with the salt concentration, where a sensitivity of ≈−0.10 nm/% salt can be derived.

The thermal response of the sensing LPG structure was also studied. For that purpose, the sensing head shown in Figure 1 was placed into a freezer to cool down to around 0°C, and it was then located into a furnace that allowed the temperature to rise smoothly to 75°C. The results are shown in Figure 6. It is evident that the wavelength resonance shift is approximately linear up to ≈50°C with a slope of ≈40 pm/°C. At this temperature, there is an abrupt change, certainly due to some thermally induced mechanical adjustment in the sensing structure. From 55°C to 75°C, the behavior stays approximately linear, with an adjusted slope of ≈60 pm/°C. Considering that the sensing head was designed for application in aqueous environments, the important temperature range is between 0°C and 30°C. For that region, the thermal sensing behavior is fairly linear and reversible, with a coefficient (≈40 pm/°C) that is different from the one found in a free LPG written in standard SMF28 fiber (≈70 pm/°C). This difference is certainly due to the fact that the LPG in the sensing head is under tension, and therefore, the thermally induced shift of the LPG resonance is also affected by the thermal behavior of the sensing head mechanical structure.

5. Conclusion

In this work, a sensing head was developed that is based on an LPG and a compact and robust metallic structure with characteristics adjusted to remote operation in aqueous environments. The refractive index sensitivity of the structure translates into a salinity sensitivity of ≈−0.10 nm/% salt, for salt concentrations in the range of 0% to 19%. The temperature cross-sensitivity effect was characterized and determined to be the important contribution of the thermal behavior of the sensing head mechanical structure. The assembly flexibility and the mechanical stability of the sensing head are positive features when considering its application in harsh aqueous ecosystems.

Acknowledgment

The authors acknowledge the contribution of João Martins, who projected the mechanical system for the sensing head.

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Biographies

Catarina Silva graduated in materials engineering by the Faculty of Sciences and Technology from the New University of Lisbon in 2003, Portugal. In 2007, she received her Master of Science in optoelectronics and lasers by the Faculty of Sciences of the University of Porto, Portugal. She is currently working in the physics department (Laboratory of Optics, Lasers and Systems) of the Faculty of Sciences at the University of Lisbon as a researcher in the fields of material processing by laser and modeling of the physical processes. Her current research interests include optical fiber systems, synthesis and characterization of nanostructured materials, and their application as photonic devices.

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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 a 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 in exploring the potential of optical fiber and integrated optic technologies in the development of biochemical sensors for environmental and medical applications. He has published more than 30 journal and conference papers and holds one patent.

José Luís Santos graduated in 1983 with a degree in applied physics (optics and electronics) from the University of Porto, Portugal, where he received his Ph.D. in physics in 1993 for research on fiber optic sensing. He is an associate professor in the Physics Department, University of Porto, and is in charge of the Optoelectronics and Electronic Systems Unit of INESC Porto. His main research interest is optical fiber sensing. He is a member of the Optical Society of America (OSA) and The International Society for Optical Engineering (SPIE).