Fabry–Pérot Cavity Based on a High-Birefringent Fiber Bragg Grating for Refractive Index and Temperature Measurement

C. Gouveia, P. A. S. Jorge, J. M. Baptista, *Member, IEEE*, and O. Frazão

***Abstract*—A fiber-optic sensor for simultaneous measurement of refractive index and temperature is described. The refractive index measurement is based on the visibility variations of a Fabry–Pérot interferometer. It is formed with the interfering waves generated from a low reflectivity Bragg grating inscribed on a Panda fiber and from the fiber end tip (Fresnel reflection) in contact with the liquid. The sensor is characterized by immersing the fiber tip in distilled water with different concentrations of ethylene glycol. A linear relation of the interferometer fringe visibility with refractive index variation is observed. The temperature is determined by the wavelength shift of the FBG peaks. Results show the feasibility of simultaneous measurement of refractive index and temperature and also the possibility of adjusting fringe visibility via polarization control.**

***Index Terms*—Fiber-optic interferometric sensors, refractive index, temperature, fiber Bragg grating (FBG), Hi-Bi fiber.**

I. Introduction

THE REFRACTIVE index measurement in liquids is an important issue for medical, chemical and biological applications. The Abbe refractometer is a classical method to measure refractive index based on transmission detections near critical angles related to total internal reflections [1]. Initially, limited to measurements in the visible range, the Abbe refractometer was later developed to measure refractive indices in the near-IR [2].

Bulk refractometers are not suitable for most of the applications due to their size, weight, and often the need of laboratory measurement conditions. To overcome these limitations, the study and development of alternative sensors has been the aim of research by many authors. Fiber-optic sensors are an interesting solution for this issue due to their high sensitivity, small size, and capability for on-site, real-time, remote, and distributed sensing. Several schemes for refractive index sensing using optical fibers have already been proposed. A simple fiber-optic technique based on Fresnel reflection from the fiber tip was studied to determine the refractive index in liquids by determining the ratio of the reflected signals from the fiber-air and from the fiber-liquid interfaces [3], [4]. Fiber tapers have an enhanced evanescent interaction and have long been explored for refractive index measurements by monitoring the transmitted optical power [5]. In spite of high sensitivity, however, these structures are very fragile.

Long period gratings (LPGs), on the other hand, provide evanescent interaction by exciting cladding modes. They maintain fiber integrity and are also widely used for refractive index measurement [6]. More recently, other types of RI sensors based on metal nano layers were developed. Depending on the thin-film properties surface plasmon resonance (SPR) or lossy modes resonances (LMRs) can be the sensing mechanism. In both cases, the metallic layer induces losses in the propagation of light in the fiber. SPR occurs when the real part of the thin-film permittivity is negative and higher in magnitude than both its own imaginary part and the permittivity of the material surrounding the thin film [7]. LMRs occurs when the real part of the thin-film permittivity is positive and higher in magnitude than both its own imaginary part and the material surrounding the thin film [8]. In any case, a coating has to be deployed over a fiber structure that ensures a good evanescent interaction like tapers or unclad fibers. These kinds of sensors are very sensitive to external refractive index and are very appealing for biosensing applications. However, they typically work in transmission mode and present very broad spectral resonances making multiplexing a very hard task. In spite of their lower sensitivity, fiber Bragg grating (FBG)-based configurations are more attractive for the purpose of multipoint sensing due to their very narrow spectral response.

FBG sensors have generated great interests in recent years because of their many industrial and environmental applications. Based on diffraction mechanism, the FBG can be used as fiber mirror or filter for fiber-optic sensing or communications. FBG sensors have been widely used for strain and temperature measurement [9]. Several refractometers based in Bragg gratings have been studied, where the core was exposed by etching the fiber cladding [10], [11] or by side-polishing [12] in the grating region. Other FBG based techniques supported on the application of specific coatings have also been studied [13]. Alternative techniques using tilted FBGs [14]–[17] and FBG cladding modes [18] were also presented. All these sensing schemes are

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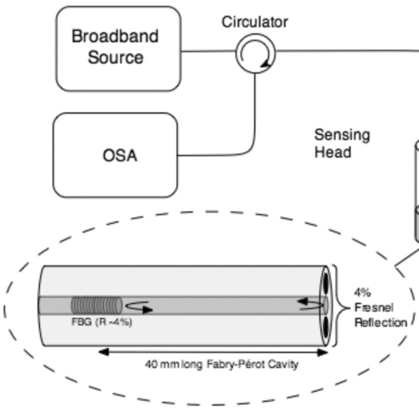

Fig. 1. Experimental setup.

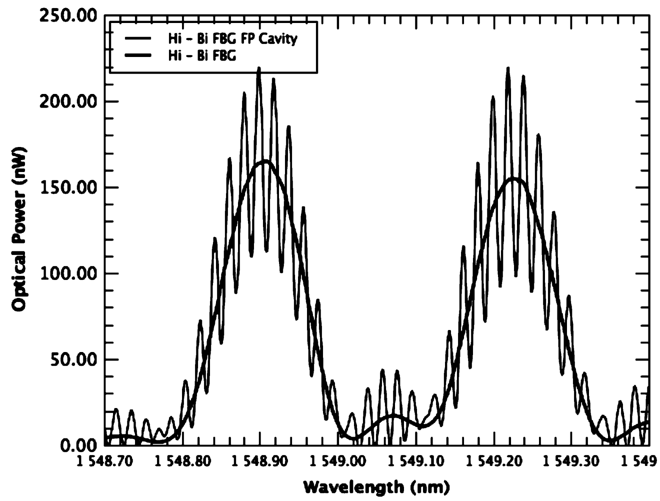

Fig. 2. Hi-Bi FBG before the cavity is created (bold) and Fabry–Pérot cavity spectra obtained after cleaving the fiber end.

based on evanescent interaction. Nevertheless, these configurations introduce fragility in the fiber sensor. A simple low finesse Fabry–Pérot cavity built with a low reflectivity FBG and the Fresnel reflection at the fiber tip was demonstrated as an effective refractometer [19]. More recently, two works were presented using a high reflectivity FBG and the Fresnel reflection at the fiber tip. In these works, the ratio between the reflected power of the grating and the reflected power in the distal end in far wavelengths was used to determine the external refractive index [20], [21].

High-birefringence (Hi-Bi) fibers are special fibers used in telecommunication networks to avoid uncontrolled changes in the polarization of the light. Due to their special characteristics, some studies have been published in sensing area to measure refractive index [22], [23].

In the present work, this concept is further explored by using a high-birefringent FBG to form a Fabry–Pérot cavity. In this situation, due to the fiber birefringence two FBGs are generated resulting in two closely spaced interference patterns each with different sensitivities to refractive index and temperature. The refractive index can be read from the visibility of the fringes' patterns and the temperature can be measured through the wavelength shift of the gratings.

II. Sensing Head Characterization

The scheme of the sensing head developed is shown in Fig. 1. The sensitive system is formed by a low-reflectivity Hi-Bi FBG structure (R $\approx 4\%$, 6 mm in length) located 40 mm away from the end tip of the fiber. The grating has been written in Hi-Bi PANDA (PM1550-HP) fiber by UV beam scanning phase mask technique. An FBG written on a PANDA fiber originates two reflection peaks at slightly different wavelengths. These arise from the fact that the birrefringent fiber presents a fast and slow axis, where the two orthogonal polarization modes experience slightly different refractive indices [24]. In order to obtain a 4% Fresnel reflection at the tip, the fiber was cleaved, perpendicular to the direction of light propagation using a standard fiber cleaver. In this situation, a low finesse Fabry–Pérot cavity was formed between the fiber end and the low-reflectivity FBG.

With the proposed configuration, the refractive index surrounding the fiber tip changes the reflectivity at the fiber tip interface and can, therefore, be retrieved from the visibility of the channeled spectrum. The visibility (V) of the fringes can be obtained by calculating $V = ((P_P - P_V)/(P_P + P_V))$, where P_P is the optical power of a peak and P_V is the optical power of a valley of the interferometric pattern. The visibility measurements are self-referred intensity measurements and therefore independent of power fluctuations. On the other hand, the FBG peaks shift in wavelength according with temperature [9], wherefore, tracking the envelope of the peaks it is possible to obtain the temperature value.

On the other hand, the FBG peaks shift in wavelength according with temperature [9], wherefore, tracking the envelope of the peaks it is possible to obtain the temperature value. The visibility change is practically independent of the temperature, and the spectral shift is independent of the external refractive index. In this way, the two parameters can be obtained from independent measurements.

Fig. 2 shows the spectra of the Hi-Bi FBG before and after the cavity is built (interference arises only after a good quality cleave is performed at the fiber tip). Analysis of the spectral output revealed two peaks, corresponding to the slow and fast axis, separated by 320 pm, each with a FWHM of 120 pm. In air, the fringes visibility was approximately 40% with a spectral periodicity of 20 pm. Characterization of the sensing probe properties was done using a simple setup where an erbium-doped fiber source illuminated the sensor through an optical circulator which enabled the reflected Fabry–Pérot signal to be observed using an Advantest Q8384 optical spectrum analyzer (OSA) with a maximum wavelength resolution of 10 pm. 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). The necessary adjustments, considering the sensing head operation at 1550 nm, can be made using the Cauchy equation with the respective coefficients [11].

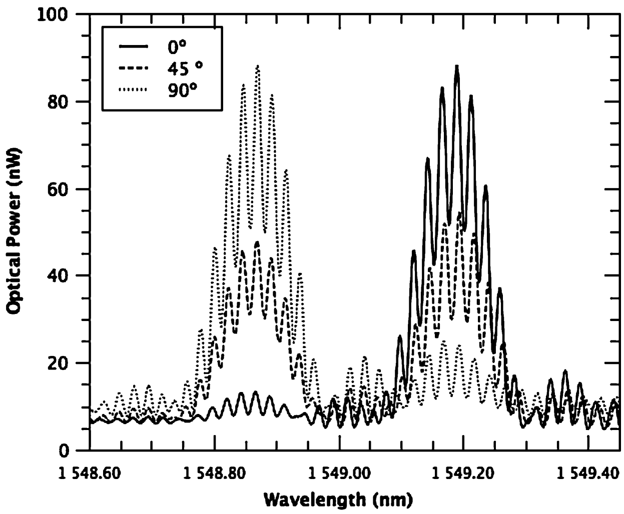

Fig. 3. Channeled spectra for different polarization angles.

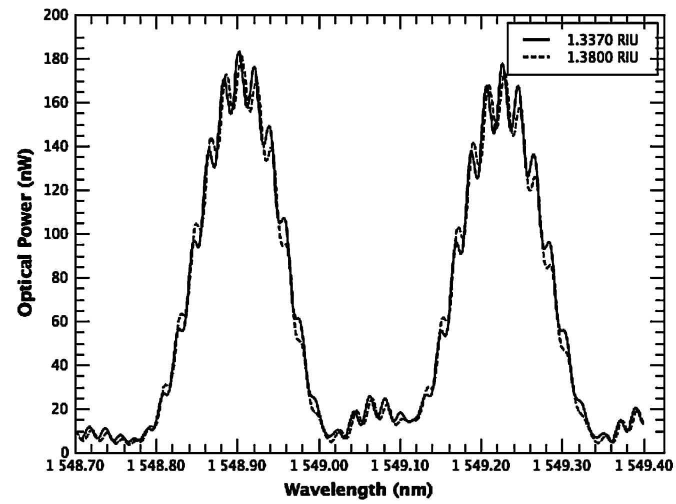

Fig. 5. Channeled spectra for two different RI solutions.

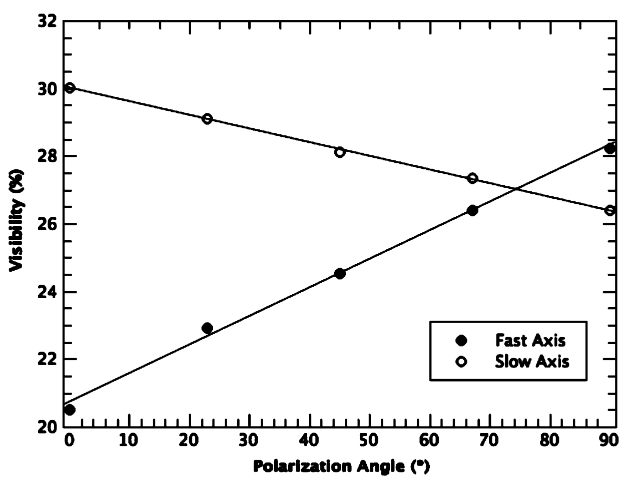

Fig. 4. Peaks visibility as a function of the polarization angles.

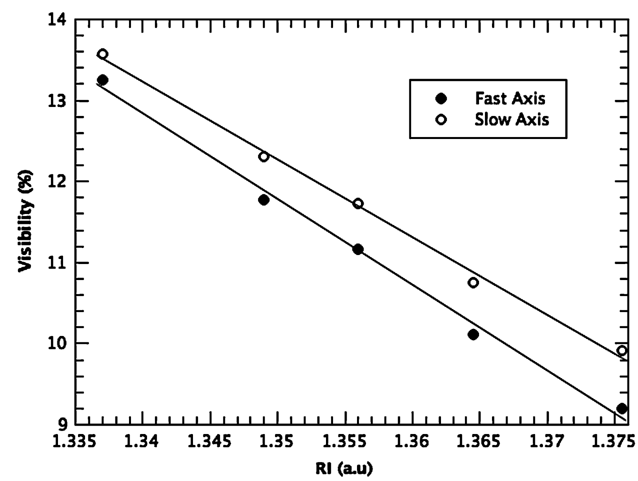

Fig. 6. Sensing head response (two peaks) for external refractive index changes.

III. Results and Discussion

The polarization effect was studied before characterization of the sensing head. For this purpose a fiber-optic polarizer and a polarization controller were inserted between the optical source and the sensing head. Polarizing the light along the birefringence axis of the fiber allows the control over the power input into each resonance being even possible to cancel one of them. This technique enables the optimization of the visibility of each peak and consequently may be used to tune the refractive index sensitivity. Fig. 3 shows the channeled spectra for different polarization angles and the corresponding visibility changes can be observed in Fig. 4. It is clear that is possible to improve de visibility and even practically cancel the peak corresponding to each axis. It is observable that the fast axis peak is more sensitive to the polarization than the slow one. In this case, the visibility can be improved by a 40% factor as compared to depolarized illumination.

Introducing the sensing head in the solution resulted in a big decrease in visibility due to the reduced index contrast at the interface. This could be compensated with polarization control. Nevertheless, for practical purposes, the sensing head was characterized using depolarized light. In this case normalization algorithms were used to track the visibility changes with higher accuracy. Fig. 5 shows the channeled spectra obtained with the sensing head inserted in solutions with two distinct refractive indices (1.3370 and 1.3800). It is observable the variation of the visibility of the interferometric fringes in the channeled spectrum, as consequence of the variation of Fresnel reflection in the fiber tip-liquid interface.

As expected, the central wavelength of the channeled spectrum is nearly independent of refractive index changes, minor changes observed were related with temperature fluctuations (approximately 15 pm drift was observed in peak wavelength which can be accounted for by a variation of temperature of approximately 1.43 °C) Nevertheless, the changes observed do not impact the visibility nor the refractive index measured. The changes of the visibility of each peak to immersion in solutions with different refractive indices are shown in Fig. 6. The decrease of the visibility is due to increase of the surrounding refractive index in the fiber tip. For the fast axis peak, an approximately linear relation between the visibility and the refractive index was found $(\mathrm{R2} = 0.99)$ with a sensitivity of

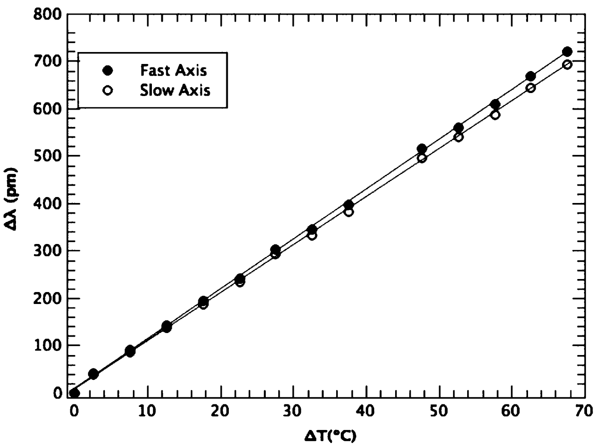

Fig. 7. Sensing head response (two peaks) to temperature.

$-1.06\%/0.01$ RIU. For the slow axis, a linear relation was also found ($\mathrm{R2} = 0.99$) with a sensitivity of $-0.96\%/0.01$ RIU. Noteworthy is the difference in sensitivity for each of the peaks ($\sim 15\%$), a relevant fact when multiparameter measurement is needed. Although reduced sensitivity was observed, some adjustments can be made to greatly improve the results such as using a grating with lower reflectivity and using polarization control to enhance visibility (by balancing the power reflected by the grating with the Fresnel reflection). In similar configuration proposed by Silva *et al.* [19], using standard SMF 28 fiber, a resolution of 10^{-3} RIU was reported. In the present configuration, similar figures should be easily attainable where in this case we have the added value of the multiparameter capability.

Also, using a shorter FBG and, therefore, broader spectra FBG in this application can facilitate visibility analysis by reducing the effects of the fringe amplitude modulation. For temperature characterization, the sensing head was immersed in distilled water. Fig. 7 shows the response of the sensing head to temperature in the 20 °C to 90 °C range. There is a linear relation between the temperature and peak wavelength of both peaks of FBG, both with $\mathrm{R2} = 0.999$. Again, the peaks show slightly different sensibilities ($\sim 4\%$), the fast axis peak shifts in wavelength 10.52 pm/°C and the slow axis 10.13 pm/°C. No changes in visibility were observed as the impact of the refractive index dependence with the temperature is too small to be measurable by this configuration.

Some preliminary tests were also made for pressure sensing as Hi-Bi FBG are known to be sensitive to this parameter. The sensing head was submitted to pressure in a closed chamber between 0 and 6 bar. While a wavelength shift of 20 pm of the envelope was noted in this range, no calibration was performed, due to the reduced sensitivity. Nevertheless, sensitivity can be improved using other types of Hi-Bi fiber for the fabrication of the sensing head.

IV. Conclusion

In this work, a compact Fabry–Pérot cavity to measure liquid refractive index and temperature is described. The structure is based on a low-finesse Fabry–Pérot interferometer with interfering waves generated by a low reflectivity Hi-Bi Bragg grating written in a PANDA fiber and the fiber-end Fresnel reflection. The results show that each peak has different sensitivities for refractive index (visibility) and temperature (wavelength shift), allowing the possibility of simultaneous measurement of refractive index and temperature. In addition, preliminary results indicate the possibility of also measuring pressure. In this context, the proposed configuration due to simplicity, low cost, small size, operation in reflection and multiplexing capability, can potentially be used as a multiparameter sensing head for temperature, pressure and refractive index (or salinity). Its application can be interesting, for instances, in oceanographic applications for acquisition of in-depth temperature and salinity profiles.

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