Fiber Bragg Grating First- and Second Order Diffraction Wavelengths based Transducer Optimized Design

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ABTRACT

Several experimental demonstrations of a unique Fiber Bragg Grating (FBG) based transducer for strain and temperature have been made. The proposed technique is based on the inscription of an unique uniform FBG what presents first- and second-order diffraction wavelength response. The measurement of the wavelength change at both wavelengths allow the design of a simple and efficient fiber optic based transducers. Although strain-temperature discrimination feasibility have been proved previously, the errors associated to the transfer matrix must be improved to achieve a similar performance than other FBG based discrimination techniques. Up to our knowledge, theoretical analysis which allows an optimized transducer design have not been made. In this communication a generalized study of the behavior of two wavelength measurement based transducers is going to be made. Physical parameters which are involved in the transducer construction are going to be analyzed and a suitable technique for optimal transducer design is going to be proposed. Several conclusions about the relation among each FBG based transducer parameter and the transfer matrix condition are going to be presented. The measurement errors associated to this physical parameters will be derived allowing the design of optimized specific transducers.

Keywords: First- and second-order diffraction, Temperature-strain discrimination, Fibre Bragg Gratings, Fiber optic transducer

1. INTRODUCTION

A large amount of effort have been made last years in the development of FBG based transducers for strain and temperature measurement. These devices allow the attainment of these magnitudes by measuring the change in the reflected Bragg wavelength. However, as both physics magnitudes produce comparable wavelength changes, it's not possible to separate these effects when both physic magnitudes have a quasi-static variation. Up to date, several strain-temperature discrimination techniques have been developed with different levels of success [1]. The use of two different FBG's , one of them fixed to the structure to make the measurement of both strain and temperature and another FBG separated from the structure to make the temperature compensation is a suitable solution [2]. However, the transducer head size is appreciably increased with this method and also a larger use of spectrum is made. To reduce the size of the transducer a dual-wavelength writing technique can be used [3]. A two step writing inscription must be used and although a more rational use of the spectrum is made it involves a more complicated writing process. This drawback can be overcome making use of the non-linear change of the refraction index of the optical fiber under UV exposure[4]. As it exists a saturation effect in this index change the resulting index profile of the FBG in the core of the optical fiber doesn't have a sinusoidal shape. A first- and second-order diffraction wavelength are expected from this structure. One at primary inscription Bragg wavelength and the other at one half this wavelength. The existence of the secondary wavelength was first demonstrated by Xie et al [5] and it was proposed for a strain-temperature discrimination scheme by Brady et al. [6]. The measurement errors obtained with this transducer approach depends on the several factors as are the primary wavelength and the type of fiber used for the FBG inscription. This work makes an effort in analysing all of these parameters and proposing an optimising method for this type of transducers.

2. STRAIN-TEMPERATURE DISCRIMINATION USING TWO WAVELENGHTS

For the simultaneous measurement of strain and temperature with a transducer it's necessary to obtain two observable parameters. The behavior matrix which relates both parameters (ϕ_1, ϕ_2) with the magnitudes of interest (T, ε) is represented as [7]:

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$$\begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix} = \begin{bmatrix} K_{1T} & K_{1\varepsilon} \\ K_{2T} & K_{2\varepsilon} \end{bmatrix} \begin{bmatrix} T \\ \varepsilon \end{bmatrix} \quad (1)$$

where K_{1T} and $K_{1\varepsilon}$ are the temperature and strain sensibilities of the first measured magnitude and $K_{2\varepsilon}$ and K_{2T} are the temperature and strain sensibilities for the second measured magnitude. The change in the first- and second order diffraction wavelengths are the measured magnitudes in this transducer approach. In order to recover the information (T and ε) the transfer matrix inversion must be possible. That is, the determinant must not equal to zero which implies that the two linear equations of the transfer matrix should be independent. The measurement errors depends on the value of these sensibilities. If a small variation range of the physical magnitudes is considered, a linear simplification of the behavior of the transducer can be supposed. In this case, the strain and temperature sensibilities of the Bragg wavelength change can be expressed as:

$$\bar{S}_\varepsilon = \frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial \varepsilon} = 1 - p_e \qquad [\text{pm}/\mu\varepsilon.\mu\text{m}] \quad (2)$$

$$\bar{S}_T = \frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial T} = \alpha + \xi \qquad [\text{pm}/^\circ\text{C}.\ \mu\text{m}] \quad (3)$$

where $\bar{S}_\varepsilon$ and $\bar{S}_T$ are the Bragg wavelength strain and temperature coefficients respectively, p_e is the effective photo-elastic coefficient, α is the thermal expansion coefficient and ξ is the thermo-optic coefficient of the optical fiber. It's noteworthy that if all of this coefficients are independent from wavelength no two wavelengths based discrimination scheme is possible. Fortunately, photo-elastic and thermo-optical coefficients are wavelength dependent [8][9]. The level of dispersion of this coefficients with the wavelength obtained in a specific fiber depends on several factors as are, the existence of a hydrogenation process, the UV exposure process, the GeO_2 concentration in the fiber, the curing process, the existence of codopants in the fiber, etc. All of these factors produce different dispersion profiles that can be deduced from experimentally characterizations and a suitable model can be obtained. Figures 1 show the effective photo-elastic and the thermo-optical coefficients for two different models [3][6] of fiber which have been derived from experimentally obtained values.

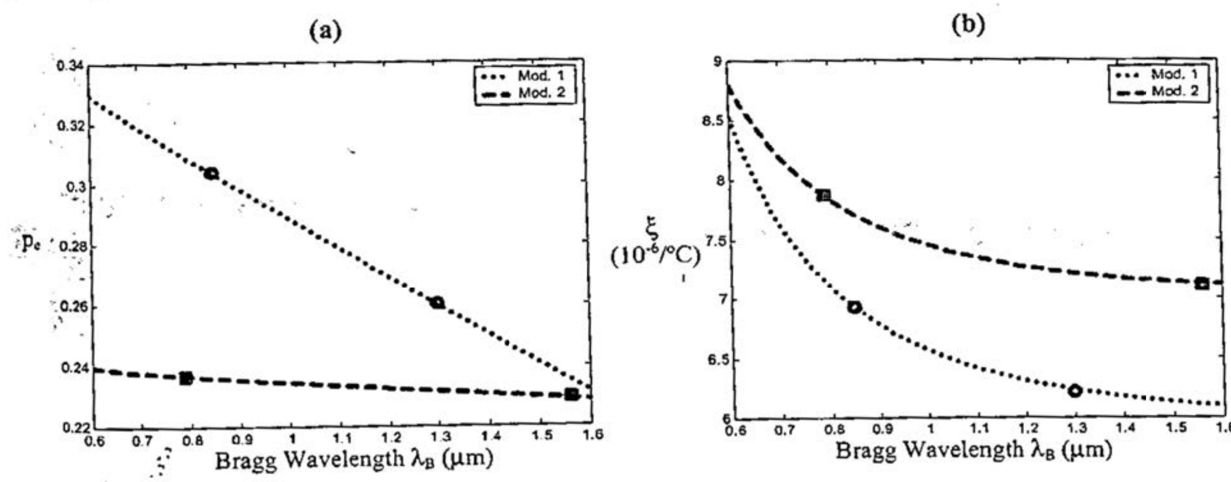

Figure 1. Models of the (a) effective photo-elastic coefficient p_e and (b) the thermo-optic coefficient ξ as a function of the Bragg wavelength for two different optical fibers. Circle [3] and square [6] marks are the experimentally obtained values for these fibers.

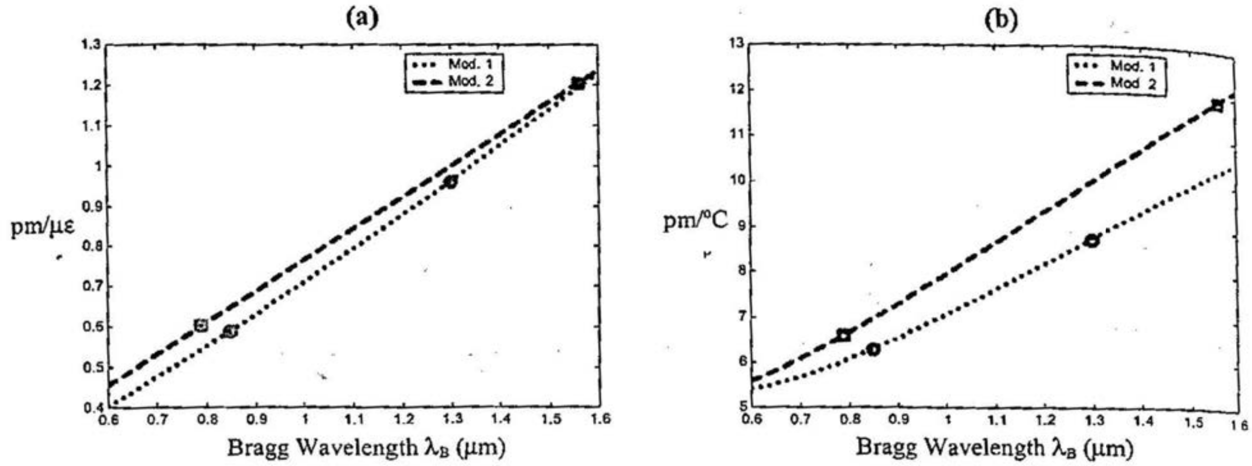

Figure 2. (a) Strain and (b) temperature coefficients as a function of the FBG Bragg wavelength for two different optical fibers. Circle [3] and square [6] marks are the experimentally obtained values for this fibers.

Once the model for a specific fiber is obtained, both temperature and strain sensibilities can be evaluated for each wavelength chosen as is depicted in figure 2. Combining the obtained sensibilities for two different Bragg wavelengths a transference matrix can be calculated. And finally, the matrix condition number and the measurement errors can be easily derived. Figures 3 shows the condition number of the matrix obtained for these models as a function of two Bragg wavelengths λ_{B1} and λ_{B2}. As it can be deduced from the figures, when both wavelengths are similar the condition of the transference matrix is very large and big measurement errors should be expected. However, as the difference between both wavelengths is increased the condition number is decreased.

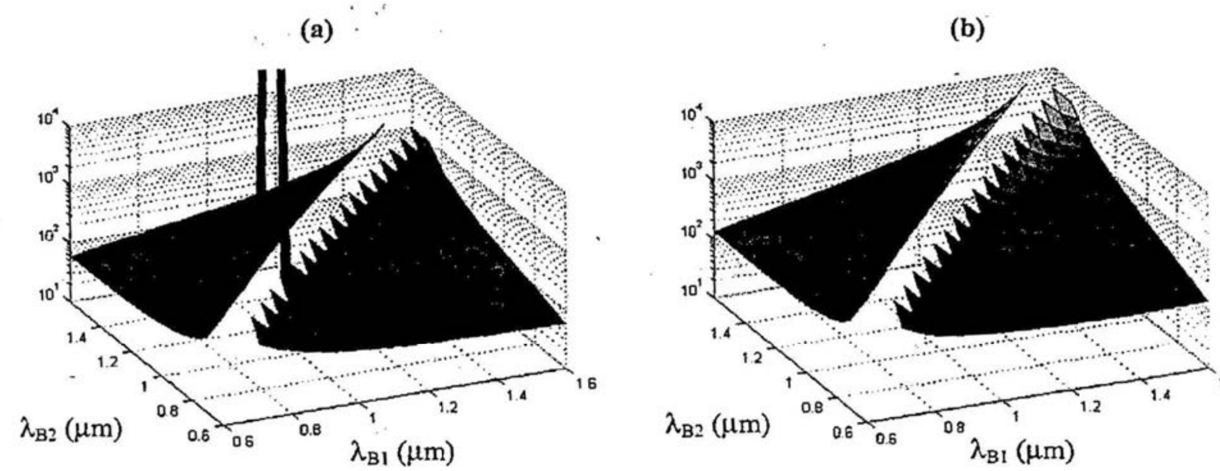

Figure 3. Condition number of the transference matrix (a) for fiber 1 and (b) for fiber 2.

As it can be observed, fiber 1 shows in general smaller condition numbers than fiber 2 demonstrating to be more suitable for strain and temperature discrimination purposes. The condition number of the transference matrix can be a good quantitative indicator of the expected measurement errors. However, as it cannot be used as an absolute characterization of the system because it only gives idea of its order [10]. The error analysis of the system is the tool that gives a precise information about it. Furthermore, as the measurement magnitudes of interest aren't homogenous it's important to calculate the errors in the units of this magnitudes.

If only the errors made with the measurands acquisition system are considered and the matrix coefficients attainment errors are negligible the measurement errors of the system can be significantly simplified [7]. Figure 4 shows the strain and measurement errors for two FBG written in a type 1 fiber for 1 pm resolution acquisition system. As it was suggested before from the matrix condition number results when two FBG Bragg wavelength are similar high measurement errors are expected. The performance of the system is improved as more dissimilar Bragg wavelengths are chosen. However, as it can be derived from the observation of the level curves of the graphs a non straightforward improvement is obtained changing linearly the FBG Bragg wavelengths.

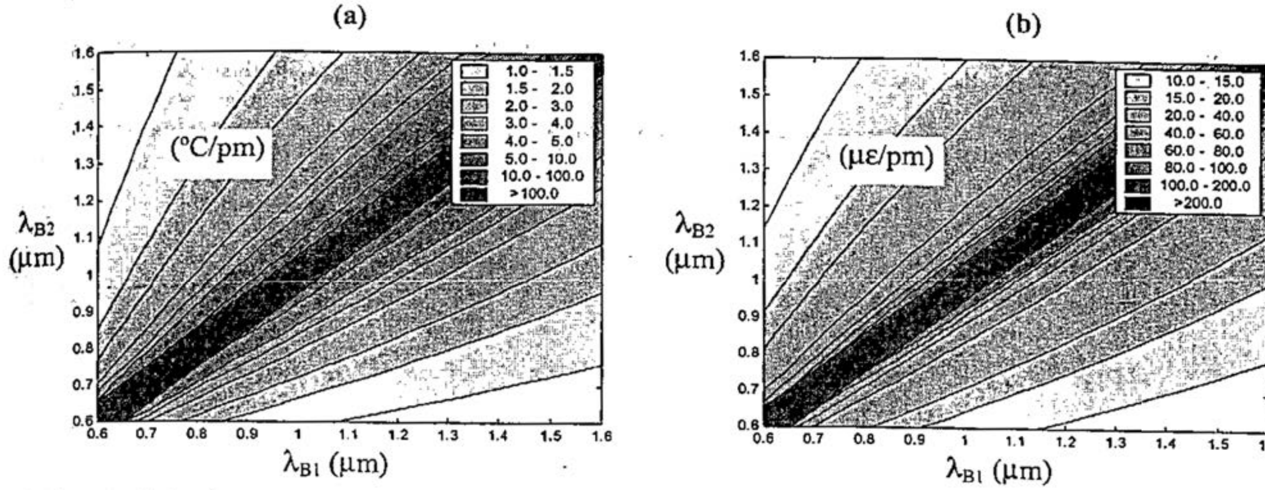

Figure 4. (a) Strain and (b) temperature measurement errors for type 1 optical fiber as a function of two FBG Bragg wavelengths. 1 pm resolution of the acquisition is supposed.

This situation is complicated by the fact that the errors scenery changes when a different type of fiber is used for FBG inscription. Figure 5 shows the strain and measurement errors obtained for a type 2 optical fiber as a function of the two FBG Bragg wavelengths chosen for 1 pm resolution acquisition system. The improvement of the performance of the system is visibly not linear with the difference between λ_{B1} y λ_{B2}.

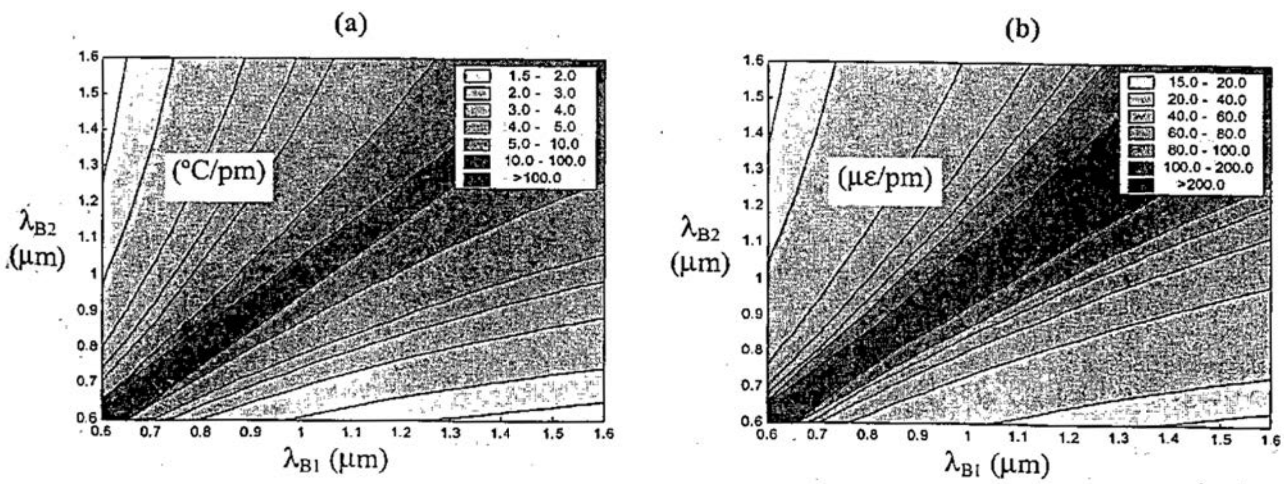

Figure 5. (a) Strain and (b) temperature measurement errors for a type 2 optical fiber as a function of two FBG Bragg wavelengths. 1 pm resolution of the acquisition is supposed.

The results obtained shows that an optimised FBG based transducer can be developed using to [illegible] in the optical fiber. This technique can be used to make a transducer head with two different FBG written at different positions. Both FBG can be fixed to the structure to be measured as they have different strain and temperature sensibilities that allows a predictable performance of the system. The consequence of this fact is that the construction of the transducer head is greatly simplified. Another possibility is the use of two superimposed FBG inscription. Although the fabrication of the device can be more complicated the transducer head is appreciably diminished.

3. FIRST– AND SECOND-ORDER DIFFRACTION WAVELENGTHS APPROACH

As it was stated before, the use of the first- and second order diffraction wavelengths approach have the advantage over other explained techniques that on one hand the transducer size is minimised and on the other had the transducer fabrication process is greatly simplified. The UV exposure process can be monitorized to obtain enough reflecting power at both wavelengths while FBG bandwidth is maintained at enough small level for wavelength interrogation purposes [4] [11]. In this case, only the primary or the secondary Bragg wavelengths can be chosen while the other is derived from the first one.

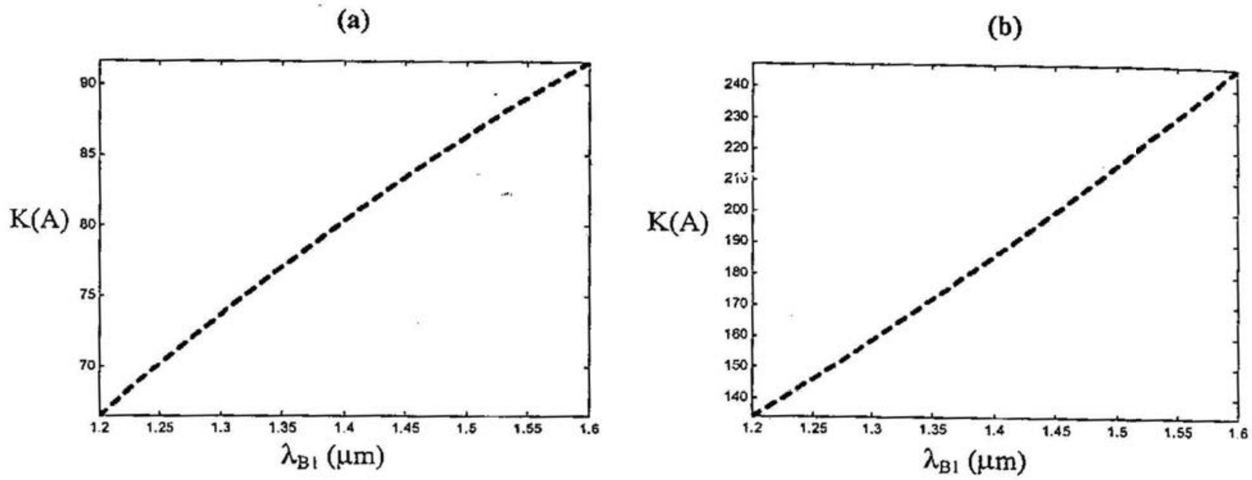

Figure 6. Condition number *K(A)* of the transference matrix (a) for fiber 1 and (b) for fiber 2 using first- and second order diffraction approach.

A calculation of the condition number *K(A)* of the transference matrix for fiber 1 and 2 is shown in figure 6. First, a primary Bragg wavelength has been supposed. Second, a secondary Bragg wavelength has been calculated. After that, the sensibilities at both wavelengths for strain and temperature forms a transference matrix whose condition number is computed. Analyzing this figure, it can be concluded that fiber 1 has better performance for this transducer purpose. However, as it was stated before, precise strain and temperature errors cannot be inferred from this computation. Figure 7 shows the strain measurement errors obtained using Jin et al. methodology when only resolution of the acquisition system is taken into account[7]. As it would be expected obtained errors for fiber 1 are always smaller than those obtained for fiber 2. Furthermore, in cases, debt to the similar dispersion models for both photo-elastic and photo-elastic coefficients which can be found for the fibers, the best performance of the transducers are found when lower wavelengths are used.

Similar conclusions can be deducted when temperature errors are calculated. Figure 8 shows the simulated measurement errors obtained for both types of optical fibers. Type 1 fiber again has the smallest errors and better performance in both cases is obtained when smaller primary Bragg wavelengths are used in the transducer design. It's noteworthy that when both measurement magnitude errors are analyzed in detail type 2 optical fiber shows a linear degradation of the strain and temperature errors while type 1 optical fiber doesn't exhibit the same behavior. There is a small range at larger wavelengths when the obtained errors are similar.

y there is another important characteristic that it must be noted. Although, the physic magnitudes which has to be asured have different units, when strain and temperature performance of the two optical fibers are compared errors tained for type 1 optical fiber is approximately the half than type 2 one, showing than performance characteristics egrade likewise for both magnitudes.

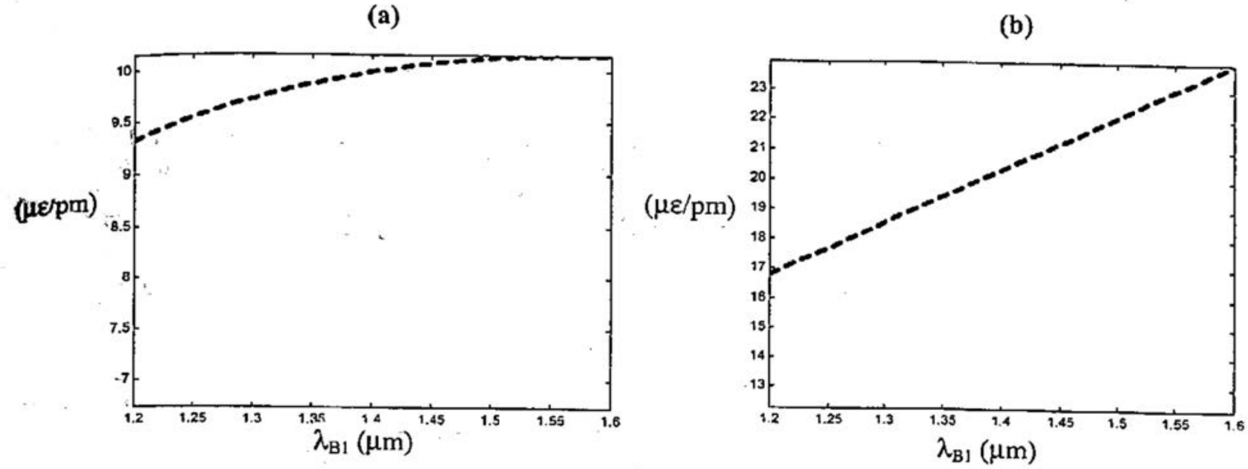

Figure 7. Temperature measurement errors for type 1 (a) and type 2 (b) optical fiber as a function of primary FBG Bragg wavelengths using first- and second order diffraction approach. 1 pm resolution of the acquisition is supposed.

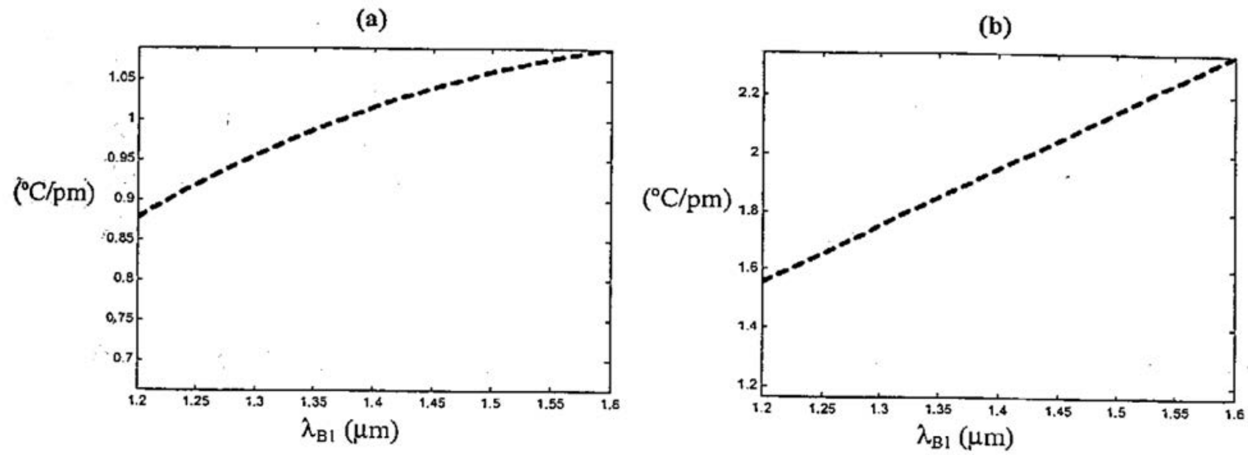

Figure 8. Temperature measurement errors for type 1 (a) and type 2 (b) optical fiber as a function of primary FBG Bragg wavelengths using first- and second order diffraction approach. 1 pm resolution of the acquisition is supposed.

4. CONCLUSIONS

A generalized study of the performance of FBG transducers designed with two wavelengths approach has been made. The analysis has been obtained though the strain and temperature measurements errors of the transducer. A experimentally based model for two types of fibers has been derived and interrelated with physical photo-elastic and themo-optical models. The analysis performed allows to characterize each fiber performance for this type of FBG transducer application. Furthermore, when two Bragg wavelengths inscription is involved lower Bragg wavelengths must be chosen to obtain a better performance of the system, whichever fiber is used. As a final results, first- and second order diffraction approach performance simulation has been made. The obtained results show there is also a better behavior when lower Bragg wavelengths are chosen. However, the strain and temperature behavior as a function of the chosen wavelength isn't the same for both types of fibers analyzed. First type of optical fiber doesn't show a linear degradation of the transducer performance with the wavelength change. It exist an small range at higher wavelengths when there isn't temperature measurement error variation. This suggests a more deep analysis of different types of fibers to find a sharp performance behavior in order to obtain similar characteristics in WDM sensor systems.

5. ACKNOWLEDGEMENTS

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