Simultaneous sensing of strain and temperature for fiber optic sensors

Prof. Sangeetha.N , Mohit Kakkar(1) , Anirudh Tiwari

(1) School Of Electronics Engineering, Vellore Institute Of Technology, Vellore, Tamil Nadu -632014

kakkar.m7@gmail.com , +919626393768

Abstract: Several inherent advantages that make sensing technologies based on optical fiber attractive for a wide range of industrial sensing applications. FBG(Fiber Bragg Grating) is used as main sensing component. Our work is to find out and analyse these FBG sensors and its behavior in the harsh environment for monitoring the large structures such as bridges, pipelines, flow lines, oil wells and dams. The effects that they face and how to combat these harsh environment effects so that the sensors work in these real time practical scenarios.

One FBG sensor can be used in normal sensing procedure to sense only temperature or strain at a time. The analysis also includes to theoretically design a FBG system which can measure both temperature and strain simultaneously.

Keywords: Fiber bragg grating , strain , temperature , simultaneous sensing , optical sensors , structural health monitoring , wavelength shift , multimode fiber

INTRODUCTION

Sensing technologies based on optical fiber have several natural advantages that make them attractive for a wide range of industrial sensing applications. They are typically small in size, inert, resistant to electromagnetic interference, resistant to harsh environments and have a ability to perform distributed sensing. Because of their telecommunication origins, fiber optic-based sensors can be easily integrated into large scale optical networks and communications systems.

Although developed initially for the telecommunications industry in the late 1990's, fiber Bragg gratings (FBGs) are increasingly being used in sensing applications and are enjoying widespread acceptance and use. The FBG(fiber bragg grating) is an optical device that acts as a filter and reflects light of a precise wavelength and exists inside the core of an optical fiber waveguide. The modulation of the refractive index or the periodic variation that is present within the fiber core decides the wavelength of the light that will be reflected. This grating assembly acts as a band-rejection optical filter that reflects wavelengths that satisfy the Bragg condition of the core index modulation and passes all the rest wavelengths of light that are not in resonance with it.

Being a optical device, an FBG sensor is unaffected by electromagnetic interference (EMI) that often effects electronic sensors. It is fairly cheap to produce, simple, small in size, lightweight, and self-referencing with a linear response. It is also preferably suited for measuring temperature and stress in possible harsh environments because of its inert nature. [1]

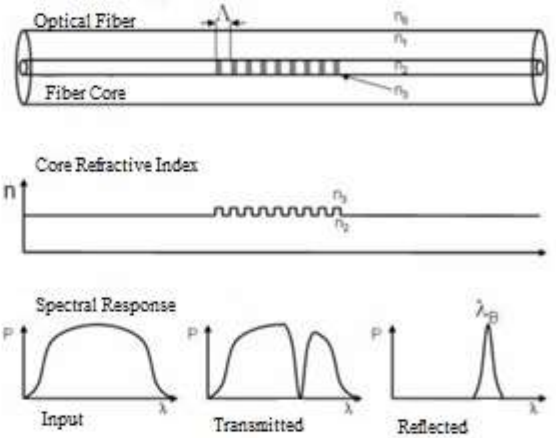

Figure 1. Schematic diagram of an FBG having an index modulation of spacing Λg inside a single-mode optical fiber.

PRINCIPLES AND TYPES

Optical fiber are mostly used to transmit light over large distance with the least amount of loss. They are sensitive to their environment as well as their state, which makes them appropriate to be used as sensors. Optical fibers have two important components: cladding and core. Core works as the passageway for the light to travel along the length of the fiber, while the cladding region with lower RI than core, supports the core region physically. The cladding region's primary function is to decrease the loss of light escaping during its transmission. When embedded into composites, polyamide coating is done on the fiber, so that they can withstand harsh environments.

There are basically two types of fiber optic sensors: intrinsic and extrinsic. Intrinsic are those ones in which the sensing takes place in the fiber itself and light never goes out of the fiber. In the extrinsic fiber optic sensors the sensing takes place in a region outside the fiber, the light has to leave the fiber and reach sensing region outside it and then it comes back to the fiber. The information about the state of the optical fiber is attainable from the light being transmitted through the core of optical fiber. The information is carried as change in the, phase, intensity, polarization, frequency, wavelength or modal distribution of the propagating light. These sensors are categorized according to the property of light being affected during sensing as interferometric, intensiometric, polarimetric, spectrometric and modalmetric.

STRAIN AND TEMPERATURE SENSING IN FBG

The sensing function of an FBG begins from the sensitivity of both the grating period and the refractive index of the optical fiber within the fiber to superficially applied thermal or mechanical changes. As the light reflected from the Bragg grating is dependent upon the spacing of the index modulation the refractive index $neff$ and the index modulation ΛG, the response of FBG is affected by the strain field, through the expansion and compression changes of ΛG and through the strain-optic effect, *i.e.*, the strain-induced change in the glass refractive index. A schematic of a basic Bragg-grating based sensor system is shown in Figure 2.

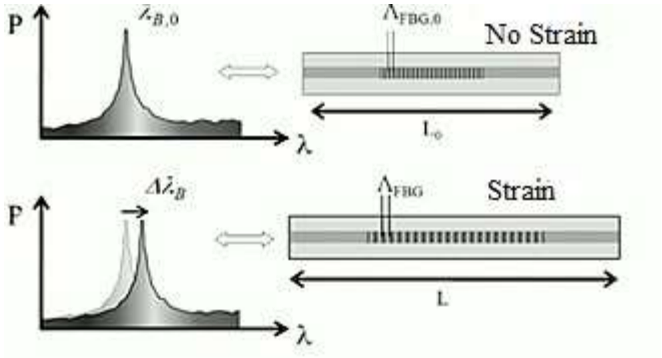

Figure 2. Basic Bragg grating-based sensor system for strain induced shift.

Because FBGs have variable resonant wavelengths, they can be multiplexed into a sensor web where different temperature and stress can be measured at different locations along the length of optical fiber. Making use of this capability, Bragg grating sensors have been incorporated into aircraft, oil pipelines, naval ships, civil structures *etc*.

The temperature sensitivity of the FBG is primarily because of the thermo-optic effect *i.e.*, temperature induces change in the glass refractive index and to a lesser amount, on the thermal expansion coefficient of the fiber. [2]

Thus, $\lambda_B$shifts by an amount $\Delta\lambda_B$in response to strain ϵ and temperature change ΔT by :

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e\epsilon + \left[P_e\left(\alpha_s - \alpha_f\right) + \zeta\right]\Delta T$$

Where, $\alpha_s$and$\alpha_f$are the thermal expansion coefficients, *Pe*is the strain-optic coefficient of any fiber bonding material and of the optical fiber itsel and thermo-optic coefficient is ζ.[3]

FBGs have variable resonant wavelengths, they can be multiplexed into a sensor web where different temperature and stress can be measured at different locations along the optical fiber length. Making use of this ability, Bragg grating sensors have been incorporated into aircraft, oil pipelines, naval ships, civil structures as ‘smart skin’ sensor webs to measure ‘*in situ*’ stress and temperature of these structures.

DESIGN APPROACH AND DETAILS

Design approach :

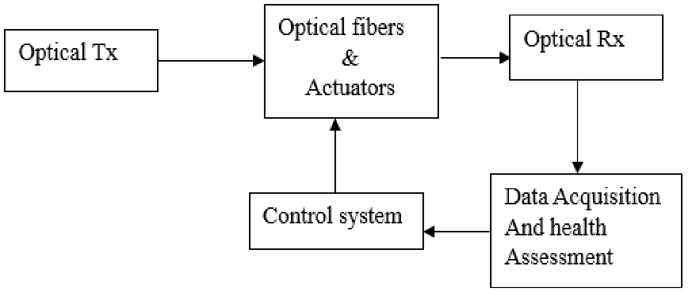

Figure 3 : Block diagram of optical fiber sensor system

The basic block diagram of an optical fiber sensor system is shown in the above figure (fig.3), after the transmission is done, the wavelength passed through the optical fiber is analysed and the wavelength shift occurring in case of the strain, temperature or harsh environment is noted, if exceeding a specific unsafe value as in the case for structural health monitoring, the essential steps can be taken to oppose the temperature, strain or harsh circumstances for the safety of the arrangement.

The wavelength used in the design approach is that of the 3rd region i.e 1550nm .we are using it because this region has the least attenuation of 0.2dB/km. This is because of the absorption characteristics of material of the glass used in fibers. For short wavelengths Rayleigh scattering of in homogeneities becomes important and towards UV wavelengths electronic absorption starts to boot in. OH^- groups show strong absorption around 1400 nm. This leaves two regions for telecommunication with similarly low absorption: first around 1300nm and second around 1500nm. For larger wavelengths infrared absorption starts to boost and as the 1500nm region has lesser attenuation than 1300nm, we use this region.

Design of the sensing system

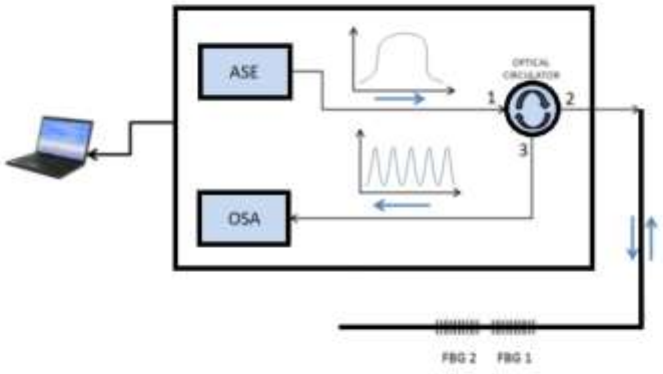

Figure 4 : The setup used to implement the FBGs is shown in Figure

The solid square represents the optical system comprise of a commercial Bragg Meter that consists of an ASE (Amplified Spontaneous Emission) broadband source used to illuminate the FBGs via Port 1 of the optical circulator. The reflection band of the FBGs returns through Port 2 and is directed through Port 3 to an implanted OSA (Optical Spectrum Analyzer) where the reflected spectrum is detected and measured. [5].

Analysis of strain and temperature sensitivities of Fiber Bragg sensor

We are using here a multimode fiber with core as silica and cladding as copper and effective refractive index as 1.46 of core.

For strain sensitivity v/s refractive index :

$s = 1-P_{eff}$;
$P_{eff} = (((N_{var}{}^2)/2) \times 0.19$;
$N_{var} = 1+(i-1) \times 0.5$;
$I = 0$ to n ;
$n = 20$;

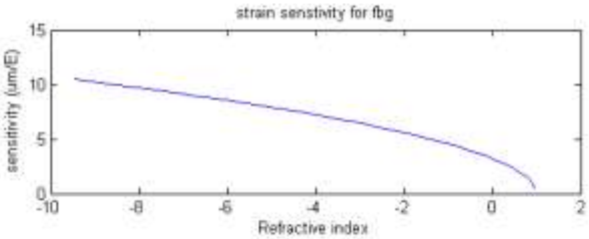

Figure 5(a) : Strain sensitivity for FBG v/s Refractive Index

Advantage of Bragg sensor is that the Bragg's wavelength is a direct(linear) function of the measurand. Increasing change in the R.I , the sensitivity falls for the FBG sensor.

For temperature sensitivity v/s wavelength=

$$\frac{\Delta\lambda_{B,T}}{\Delta\lambda_B} = \frac{1}{\lambda_B}\frac{d\lambda_B}{dT} = (\frac{1}{n_{eff}}\frac{\delta n_{eff}}{\delta T} - \frac{\delta {n_{eff}}^2}{2}(p_{11} + 2p_{12})\alpha T + \alpha T)$$

Where the thermal expansion coeff. of silica fiber is about: α=0.5 x 10^{-6} x K^{-1}
Pockel's coefficients p11 and p12 are eaual to 0.113 and 0.252, respectively in optical fiber.
Neff depends on wavelength and R.I profile but can normally be estimated to be 1.46.
δ neff/δT is the thermo optical coefficient.
the partial derivative δ neff/δT is equal to 9.7 x 10^{-6}.

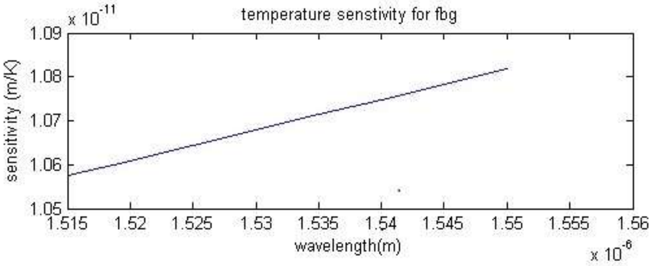

Figure 5(b) : Temperature sensitivity for FBG v/s wavelength

Theoretical value of sensitivity obtained is 10.8 pm/k at 1550 nm , It is also verified from the graph obtained through the equation analysis in MATLAB [6].

Simultaneous measurement of strain and temperature

The problem encountered in measuring strain and temperature simultaneously has been solved in this section using fiber Bragg grating (FBG) sensor.[7]
This hybrid sensor consists of a fiber Bragg grating element superimposed on a multimode fiber.[8]
We have analytically derived the relationship of the sensor outputs to measurands (strain and temperature) and yielded the characteristic matrix of sensor.
Bragg's law defines the situation for constructive interference from numerous crystallographic planes of the crystalline frame separated by a distance *d*:

$$2d \sin\theta = n\lambda \qquad (1)$$

Where *n* is an integer, λ is the wavelength and θ is the incident angle

Equation (1), developed for space, has to be modified for silica, since the distance moved by light is affected by the refractive index of the fiber:

$$\lambda_B = 2.\eta_{eff}\Lambda \qquad (2)$$

Hence the Bragg wavelength (λ_B) of a fiber bragg grating is a function of the (η_{eff}) effective R.I (refractive index) of the fiber and the periodicity of grating (Λ).

To compute the sensitivity of the Bragg wavelength for strain and temperature we begin from Eq. (2) and find that the sensitivity with temperature is partial derivative with respect to that of temperature:

$$\frac{\Delta\lambda_B}{\Delta T} = 2\eta_{eff}\frac{\delta\Lambda}{\delta T} + 2\Lambda\frac{\delta\eta_{eff}}{\delta T} \qquad (3)$$

Substituting (2) in (3) twice we get:

$$\frac{\Delta\lambda_B}{\Delta T} = \frac{1}{\Lambda}\frac{\delta\Lambda}{\delta T} + \frac{1}{\eta_{eff}}\frac{\delta\eta_{eff}}{\delta T}\lambda_B$$

Reorganizing:

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{1}{\Lambda}\frac{\delta\Lambda}{\delta T}\Delta T + \frac{1}{\eta_{eff}}\frac{\delta\eta_{eff}}{\delta T}\Delta T$$

The first term is nothing but silica's thermal expansion (α) and the second term is the thermo-optic coefficient (η) expressing the temperature dependency of the refractive index (dn/dT). Further substituting it we have:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \eta)\Delta T \qquad (4)$$

The sensitivity with strain is the partial derivative of (2) with respect to that of displacement:

$$\frac{\Delta\lambda_B}{\Delta l} = 2\eta_{eff}\frac{\delta\Lambda}{\delta l}\Delta T + 2\Lambda\frac{\delta\eta_{eff}}{\delta l} \qquad (5)$$

Substituting (2) in (5) twice, we have:

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{1}{\Lambda}\frac{\delta\Lambda}{\delta l}\Delta l + \frac{1}{\eta_{eff}}\frac{\delta\eta_{eff}}{\delta l}\Delta l \qquad (6)$$

The first term in Eq. (6) is nothing but the strain due to the extension of the fiber in the grating period. The second term in Eq. (6) is photo-elastic coefficient (ρ_e), the variation of the refractive index with strain.

When some strain is applied to the fiber, the two terms in Eq. (6) produce contrasting effects, one increases the space between the gratings and therefore increasing the Bragg wavelength and the other one decreases the effective refractive index and consequently decreases the Bragg wavelength. The collective effect of both phenomena is the standard form of the Bragg wavelength displacement with strain:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\varepsilon_z \qquad (7)$$

where $\varepsilon_z$is the longitudinal strain of the grating.

Linking (4) and (7) together we end up with the sensitivity of the Bragg wavelength with temperature and strain:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\varepsilon_z + (\alpha+\eta)\Delta T \qquad (8)$$

Eq.(8) shows that Bragg displacement is a function of both temperature and strain. By noting only $\Delta\lambda_B$ one is not able to tell if the displacement was due to temperature, strain or both. The FBG must be safe against strain if someone wants to measure only temperature, which can be easily done by loosely introducing the FBG into a small-bore stiff tubing. Though, if strain is to be measured, it's very hard to stop variation of local temperature to reach the fiber bragg grating; instead, we have to compensate this variation.

Alternative way is by the use of some other FBG on the same fiber, secure against strain and at the same temperature as its neighbour. The two FBGs will be in the same fiber optic and will give two different bragg reflections, one depending on temperature and strain and the other depending only on temperature, for compensation.

$$\Delta\lambda_{B1} = K_{\varepsilon 1}\Delta\varepsilon + K_{T1}\Delta T \qquad (9)$$

Where

$$K_{\varepsilon 1} = (1-\rho_\varepsilon)\lambda_{b1}$$

$$K_{t1} = (\alpha-\eta)\lambda_{b1}$$

Likewise, for the other FBG we have:

$$\Delta\lambda_{B2} = K_{\varepsilon 2}\Delta\varepsilon + K_{T2}\Delta T \qquad (10)$$

Where

$$K_{\varepsilon 2} = (1-\rho_{\varepsilon})\lambda_{b2}$$

$$K_{t2} = (\alpha-\eta)\lambda_{b2}$$

Equations (9) and (10) can be written in matrix form:

$$\begin{matrix}\Delta\lambda_{B1}\\ \Delta\lambda_{B2}\end{matrix} = \begin{bmatrix} k_{\varepsilon 1} & k_{t1} \\ k_{\varepsilon 2} & k_{t2} \end{bmatrix} \text{ x } \begin{bmatrix}\Delta\varepsilon \\ \Delta T\end{bmatrix} \qquad (11)$$

Inverting the above matrix , we have the sensing matrix:

$$\begin{bmatrix}\Delta\varepsilon \\ \Delta T\end{bmatrix} = \begin{bmatrix} k_{\varepsilon 1} & k_{t1} \\ k_{\varepsilon 2} & k_{t2} \end{bmatrix}^{-1} \text{ x } \begin{bmatrix}\Delta\lambda_{B1} \\ \Delta\lambda_{B2}\end{bmatrix} \qquad (12)$$

The matrix shows the combination of FBG and MMF. All the MMF used are commercially available. The FBG used in the analysis has 1560.65 nm bragg wavelength. Temperature and strain are sensed by FBG integrated on three MMF's by sensing the change in the bragg wavelength. [10]

Each combination acts differently in sensing strain and temperature due to their different specifications. Each MMF has different numerical aperture and different core/cladding diameters. The wavelength shift is different for different MMF we can relate this shift to either blueshift or redshift. Blueshift is when the wavelength shift is decreasing. Redshift is wavelength shift is increasing.

In equation (12) we can see that whenever there is change in wavelength then we can sense the change in strain and temperature. The inverse matrix is a constant matrix for each MMF. The constants are calculated from the given specification of the MMF.

Fiber Type	Numerical Aperture range	Core/Cladding Diameter (µm)	Manufactured commercially by
MMF1	0.25-0.30	100/140	POFC
MMF2	0.27-0.31	62.5/125	POFC
MMF3	0.32-0.37	1.9/115.7	Sumitomo Electric

When there is slight change in temperature (degree Celsius) the bragg wavelength shifts, this shift is measured by the OSA used. As we can see in the graphs the first two MMF have blueshift and the third one has redshift. Fig 8(a)

Same happens in the case of strain sensing, slight change in strain (micro strain) causes the bragg wavelength to shift, the shift is in nanometers and that is measured by the OSA used. As we can see in the graphs all have redshift i.e the shifts are increasing as the strain increases. Fig 8(b)

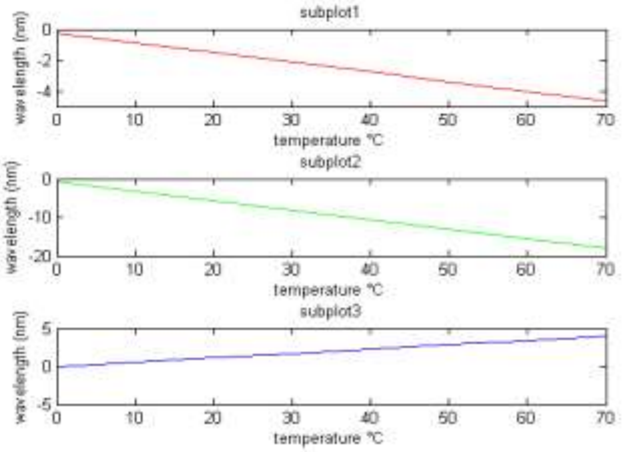

Figure 6(a) : Wavelength shifts as a function of ambient temperature for an FBG combined with three types of MMFs

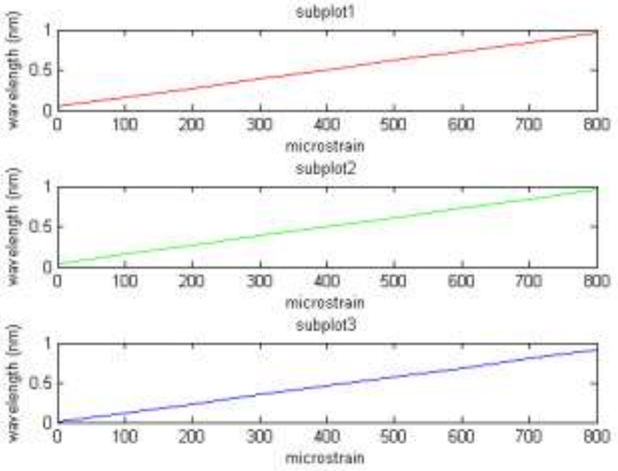

Figure 6(b) : Wavelength shifts as a function of applied strain for an FBG combined with three types of MMFs,

STRUCTURAL HEALTH MONITORING :

Every structure be it an oil well, dam, bridge, buildings etc go through some strain and temperature changes. Strain and temperature vary from point to point in these structure like in dams the strain at the base is different and strain at the gate joint is different. So if the strain threshold for the dam gets crossed then a catastrophic event may occur.

So we have to measure these parameters time to time, it cannot be done manually so we have designed a small system which measures these parameters and monitor them continuously.We just have to place our FBG sensors at the point where there are changes in strain or temperature and it would measure both simultaneously. So by this we can easily take the precaution and there are no need of routine monitoring of the structure. [11]

Any change in temperature or strain would be sensed by the sensor. This would change the bragg wavelength and by OSA we can easily check whether the values are reaching structure threshold or not.

ACKNOWLEDGMENT

I place on record and warmly acknowledge the continuous encouragement, invaluable supervision, timely suggestions and inspired guidance offered by my guide **Prof. Sangeetha.N** in bringing this project to a successful completion. I am also grateful to **Prof P.Arulmozhivarman**, Program Manager of the Department of Electronics and Communication Engineering (SENSE), VIT university , vellore for permitting us to make use of the facilities available in the department to carry out the project successfully.

CONCLUSION

While experiencing strain or temperature the bragg wavelength of the sensor changes, it either shows blueshift or redshift.

In temperature v/s wavelength shift, the first two MMF and FBG combination show blueshift but the third MMF and FBG combination gives redshift. In strain v/s wavelength shift all the combination give redshift. Hence we can easily sense temperature and strain at the same time just by monitoring the bragg wavelength shift.

REFERENCES:

Hill, K.O.; Fujii, Y.; Johnson, D.C.; Kawasaki, B.S. Photosensitivity in optical fiber waveguedes: Application to reflection filter fabrication. Appl. Phys. Lett. 2008, 32, 647–649.

Zhang, B.; Kahrizi, M. High-temperature resistance fiber Bragg grating temperature sensor fabrication. IEEE Sens. J. 2007, 7, 586–591.

Li, Y.; Yang, M.; Wang, D.N.; Lu, J.; Sun, T.; Grattan, K.T. Fiber Bragg gratings with enhanced thermal stability by residual stress relaxation. Opt. Exp. 2009, 17, 19785–19790.

Aikawa, K.; Izoe, K.; Shamoto, N.; Kudoh, M.; Tsumanuma, T. Radiation-resistant single-mode optical fibers. Fujikura Tech. Rev. 2008, 37, 9–13.

Frazão, O.; Ferreira, L.A.; Araujo, F.M.; Santos, J.L. Applications of fiber optic grating technology to multi-parameter measurement. Fiber Integr. Opt. 2005, 24, 227–244.

S. W. James, M. L. Dockney, and R. P. Tatam, "Simultaneous independent temperature and strain measurement using infibre Bragg grating sensors," Electron. Lett. 32, 1133–1134 (1996).

O. Frazão and J. L. Santos, "Simultaneous measurement of strain and temperature using a Bragg grating structure written in germanosilicate fibres," J. Opt. A 6, 553–556 (2004).

E. Li, "Temperature compensation of multimode-interferencebased fiber devices," Opt. Lett. 32, 2064–2066 (2007).

Song M. H., Lee S. B., Choi S. S., et al. "Simultaneous measurement of temperature and strain using two fiber Bragg gratings embedded in a glass tube," *Optical Fiber Technology* 3(2), pp.194-196, 1997.

Shu X. W., Liu Y., Zhao D. H., et al. "Dependence of temperature and strain coefficients on fiber grating type and its application to simultaneous temperature and strain measurement," *Optics Letters* 27(9), pp.701-703, 2002.

Hong, C. S., C. Y. Ryu, B. Y. Koo, C. G. Kim, S. H. Yun. 2000. "Strain monitoring of smart bridge using fiber Bragg grating sensor system with wavelength-swept fiber laser," in Smart Structures and Materials 2000: Smart Systems for Bridges, Structures, and Highways, S. C. Liu, Editor, Proc. SPIE Vol. 3988, pp.371-379