Use of factorial design for temperature, humidity, and strain, for characterization of FBGs

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Design of experiment is a scientific approach that provides the maximum amount of information with the minimum number of experiments. It is applicable in scientific and industrial researches. We report on the application of 3 variables 2 levels factorial design for simultaneous temperature, humidity, and strain sensing by using fiber Bragg gratings inscribed in Standard Draka Bend-Bright optical fiber. Factorial design allows estimation of sensitivity to each factor and also the effect of interaction between different factors.

Introduction

A fiber Bragg grating (FBG) is a periodic modulation of the refractive index inside the optical fiber core. When a short length of uncoated germanosilica optical fiber is exposed to a periodic distribution of UV light intensity, the refractive index of the core will be altered [1]. FBGs are investigated for different applications and are well known as sensing elements. FBGs have shown unique potential to monitor different parameters, through the modulation of light in reaction to the environment, such as strain, temperature, humidity [2–5].

The periodic modulation of refractive index in the core is a perturbation that leads to the reflection of a precise wavelength λ_B referred to as the Bragg wavelength for which the Bragg condition is satisfied:

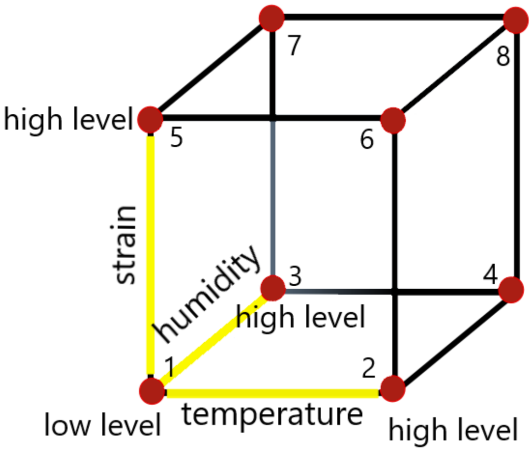
$$\lambda_B = 2n_{\text{eff}}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of fiber core for the mode of light traveling through the fiber, and Λ is the grating period.

FBGs are ideal devices for monitoring temperature and strain as variation of temperature and/or strain affects the Bragg wavelength λ_B. For humidity sensing, it can be reached if the FBG is coated with an additional hygroscopic material like polyimide that will induce strain and in turn change the Bragg wavelength.

Design of experiment is a structured and organized way of operating and analyzing experiments to evaluate the factors which affect the response. Design of experiment is feasible for physical processes and computer simulation models as well. Experimental design is an effective tool to gain maximum information from a study while the data to be collected will be minimized. Factorial design can be used when the treatments are the combination of the levels of two or more factors, that vary simultaneously. In addition, factorial design gives access to the sensitivity to each factor and to a measure of the interaction of the factors 2 by 2, 3 by 3, … [6, 7]. In our case, we study the effect of 3 factors — temperature (x_t), humidity (x_h) and strain

(x_s) — and for each factor we take two levels — high (+1) and low (−1). Thus $8 = 2^3$ experiments should be run to obtain the full picture of the FBG as shown in Figure 1. The measuring points are located at the vertices of a cube in 3-dimensions and the the trials are described by the two tables.



Trials	Factors		
	x_t	x_h	x_s
1	−1	−1	−1
2	+1	−1	−1
3	−1	+1	−1
4	+1	+1	−1
5	−1	−1	+1
6	+1	−1	+1
7	−1	+1	+1
8	+1	+1	+1

Factor	(−1)	(+1)
x_t	25 °C	65 °C
x_h	30 %rH	70 %rH
x_s	45.59 µϵ	235.14 µϵ

Figure 1 – Left: Levels of factors and points of interest to measure in 3d space, Right: Explicit schedule of the experimental points to be measured.

It is assumed that a FBG has linear response to the factors x_t, x_h and x_s, in the ranges given in the table above. Then the response, i.e., the Bragg wavelength $y = \lambda_B$, for normalized values of the variables ($-1 \leq x_i \leq +1$) is given by:

$$y = a_0 + a_t x_t + a_h x_h + a_s x_s + a_{th} x_t x_h + a_{ts} x_t x_s + a_{hs} x_h x_s + a_{ths} x_t x_h x_s \qquad (2)$$

where a_0 is the mean value of the Bragg wavelength, a_t, a_h, and a_s are the temperature, humidity, and strain coefficients, respectively. The interaction coefficients are represented by a_{th} between temperature and humidity, a_{ts} between temperature and strain, and a_{hs} between humidity and strain. Finally, the coefficient a_{ths} is the cross-interaction coefficient, 3 by 3, between temperature, humidity and strain.
Relation (2) has 8 unknowns $[a]$ and 8 measurements $[y]$ are made. It can then be shown [6,7] that the coefficients a_i can be computed from the measurements y_n without ambiguity by the relation:

$$\left[a\right] = \frac{1}{8} \begin{bmatrix} +1 & -1 & -1 & -1 & +1 & +1 & +1 & -1 \\ +1 & +1 & -1 & -1 & -1 & -1 & +1 & +1 \\ +1 & -1 & +1 & -1 & -1 & +1 & -1 & +1 \\ +1 & +1 & +1 & -1 & +1 & -1 & -1 & -1 \\ +1 & -1 & -1 & +1 & +1 & -1 & -1 & +1 \\ +1 & +1 & -1 & +1 & -1 & +1 & -1 & -1 \\ +1 & -1 & +1 & +1 & -1 & -1 & +1 & -1 \\ +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \end{bmatrix}' \left[y\right] \qquad (3)$$

Experiments and Results

Three 4 mm uniform gratings were inscribed in a singlemode Draka fiber (BendBright) by a double frequency fiber laser emitting at 244 nm,(Azur Light System coupled with an external cavity frequency double from Sirah). A ten fold beam expander and an adjustable diaphragm were used to adjust the length of the gratings. The grating were inscribed by interference technique by the Lloyd mirror setup.

The fiber was hydrogen loaded prior inscription and the 3 FBGs were thermally annealed at 100 °C for one day to eliminate the residual hydrogen and to stabilize the gratings. The first grating was left uncoated, while the second was recoated by acrylate (DSM 950 200). Finally the third one was coated by a layer of polyimide (PI2 525), followed by curing at 150 °C on a heater to remove volatile compounds. The experimental setup is depicted in Figure 2 and consists of a climatic chamber (WEISS TECHNIK-SB22^{300}, with controlled temperature and humidity) and some mechanical components to impose a controlled strain on the gratings by loading them with by different weights. A Bragg-meter from Fiber sensing (FS2 200) is used for spectrum analysis, from which a computer extracts the 8 Bragg wavelengths $y_i = \lambda_B$ corresponding to the experimental plan of Figure 1.

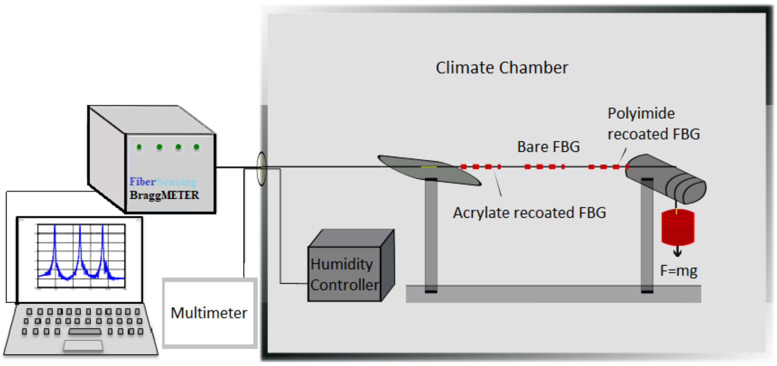


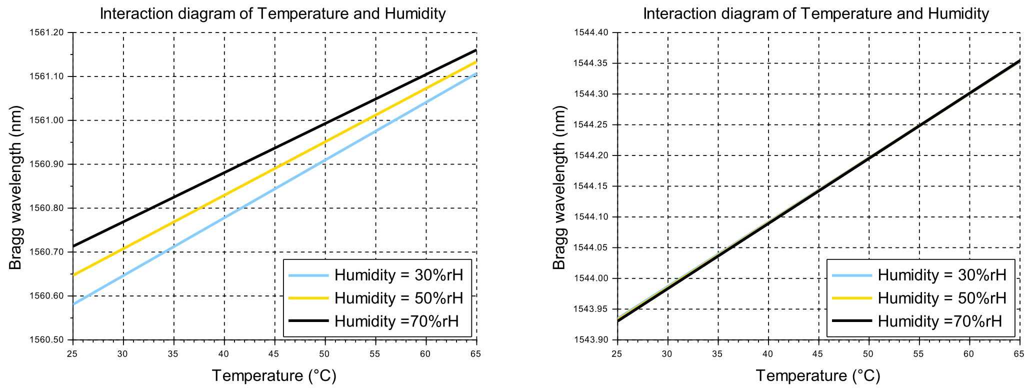
Figure 2 – Experimental setup used to impose temperature, humidity and strain on the gratings.

By applying relation (3), the coefficients a_i are computed and then de-normalized as b_i coefficients given in Table 1. It is seen that temperature and strain sensitivities are around 10 pm/°C (bare and acrylate) to 15 pm/°C (polyimide) and 1 pm/µϵ respectively. These results are very similar to those obtained by a classical measurement. Moreover, strain sensitivity is unaffected by the coating whereas there is an increase of temperature sensitivity for polyimide coating. Polyimide is also known to be a good transducer material for humidity, so the polyimide coated grating is expected to be more sensitive to humidity than the others. This result is indeed recovered in the b_h coefficients.

Table 1 – Calculated de-normalized coefficients for 3 cascaded FBGs.

De-normalized coefficients	Acrylate FBG	Bare FBG	Polyimide FBG
b_0(nm)	1 526.274	1 543.677	1 560.115
b_t (pm/°C)	10.69	10.37	14.63
b_h (pm/%rH)	−0.005	−0.17	4.54
b_s (pm/µϵ)	1.13	1.06	1.05
b_{th} (pm/(°C · %rH))	−0.002	0.003	−0.049
b_{ts} (pm/(°C · µϵ))	0.000 5	0.002	0.002
b_{hs} (pm/(%rH · µϵ))	−0.000 9	0.001	−0.000 9
b_{ths} (pm/(°C · %rH · µϵ))	-1.64×10^{-5}	-6.59×10^{-5}	-1.64×10^{-5}

One of the main advantage of the design of experiment is the easy access to the cross-sensitivity coefficients (last 4 lines of Table 1). As an example, Figure 3 shows that the temperature sensitivity depends on humidity for polyimide coated gratings (a) while the temperature sensitivity for bare gratings (b) is insensitive to humidity. Hence, humidity correction has to be done for temperature measurements with polyimide coated FBGs.



(a) **(b)**

Figure 3 – Effect of different levels of humidity on temperature sensing for (a) polyimide coated FBG, and (b) bare FBG.

Conclusion

Use of factorial design for characterization of FBGs is a powerful tools, which gives considerable amount of information with minimum number of experiments. In this study, we used factorial design to analyze FBGs and obtained temperature, humidity, and strain sensitivities, as well as cross-sensitivities that should be used for calibration.

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