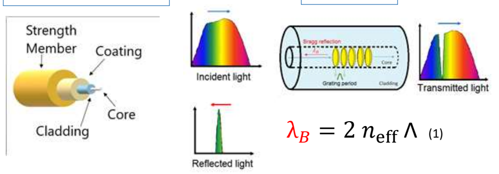
Factorial design for temperature, humidity and strain sensing using fiber Bragg grating

N. Safari-Yazd, D. Kinet, C. Caucheteur, and P. Mégret
Electromagnetism and Telecommunication Department, University of Mons, Mons, Belgium

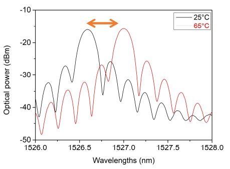
Design of experiment is a scientific approach that provides sufficient information with a minimum number of experiments. Factorial design can be used when treatments are the combination of the levels of two or more factors that vary simultaneously.

Fiber Bragg Grating (FBG) sensor

Optical fiber structure | Uniform FBG | Bragg wavelength shifts by modifications of T



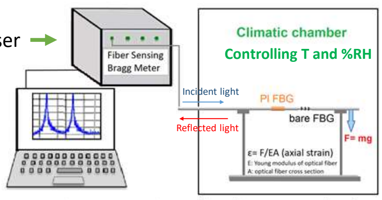
$$\lambda_B = 2\, n_{\mathrm{eff}}\, \Lambda \quad (1)$$



- FBG is a periodic modification of the refractive index in the optical fiber core.
- It can be achieved by exposure a short length of optical fiber to a UV light interference pattern
- FBG works as a wavelength selective mirror.
- Variation of temperature (T) and/or strain (ε) affect the λ_B, as both n_{eff} and Λ are T and ε dependent.
- A sensor is obtained by monitoring the $\Delta\lambda_B$ versus T and ε.
- For silica FBG temperature sensitivity is in order of 10 pm/°C, and strain sensitivity is in order of 1 pm/με.
- For humidity (%RH) sensing by FBG, it can be coated with an additional hygroscopic material like Polyimide (PI)
- Polyimide induces strain in the FBG by absorbing water and thus changes the grating period (Λ)
- Linear superposition of T, %RH, and ε effects

$$\Delta\lambda_B = S_t\Delta T + S_h\Delta H + S_\varepsilon\Delta S \quad (2)$$

Experimental Setup and Factorial design



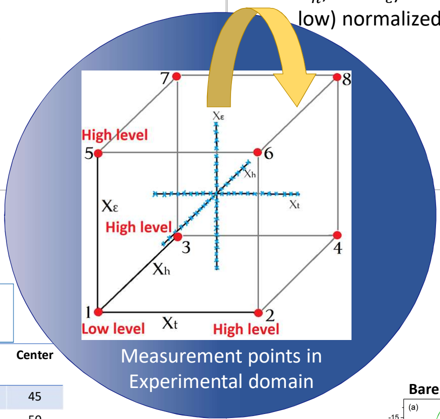
- Two uniform gratings were inscribed in a standard optical fiber by interferometric technique
- One grating was recoated by a layer of PI, second remained bare
- Factorial design collect data at the vertices of a hyper-cube in k-dimensions (number of factors)
- k factors with n levels for each one, n^k *measurement* points
- 8 combination between 3 factors (X_t, X_h, and X_ε) with 2 levels (high and low) normalized to ±1

Trials	Factors			Interaction 2 × 2			Interaction 3 × 3	Meas.
	X_t	X_h	X_ε	X_tX_h	X_tX_ε	X_hX_ε	$X_tX_hX_\varepsilon$	y
1	−1	−1	−1	+1	+1	+1	−1	λ_{B1}
2	+1	−1	−1	−1	−1	+1	+1	λ_{B2}
3	−1	+1	−1	−1	+1	−1	+1	λ_{B3}
4	+1	+1	−1	+1	−1	−1	−1	λ_{B4}
5	−1	−1	+1	+1	−1	−1	+1	λ_{B5}
6	+1	−1	+1	−1	+1	−1	−1	λ_{B6}
7	−1	+1	+1	−1	−1	+1	−1	λ_{B7}
8	+1	+1	+1	+1	+1	+1	+1	λ_{B8}

$$y = a_0 + a_t x_t + a_h x_h + a_\varepsilon x_\varepsilon + a_{th} x_t x_h + a_{t\varepsilon} x_t x_\varepsilon + a_{h\varepsilon} x_h x_\varepsilon + a_{th\varepsilon} x_t x_h x_\varepsilon \quad (3)$$

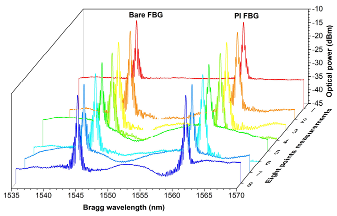
$$\mathbf{a} = \mathbf{X}^{-1}.\mathbf{y} \quad (4)$$

a: normalized coefficients
X: a matrix made from the above table



Measurement points in Experimental domain

Experimental results



Reflection spectra from 2 FBGs modifications in 8 measurement points

3 factors limited to 2 level

Factor	Low level	High level	Center
x_t (°C)	25	65	45
x_h(%RH)	30	70	50
x_s (με)	44.45	226.65	135.55

$$\Delta\lambda_B = S_t\Delta T + S_h\Delta H + S_\varepsilon\Delta\varepsilon + S_{th}\Delta T\Delta H + S_{t\varepsilon}\Delta T\Delta\varepsilon + S_{h\varepsilon}\Delta H\Delta\varepsilon + S_{th\varepsilon}\Delta T\Delta H\Delta\varepsilon \quad (5)$$

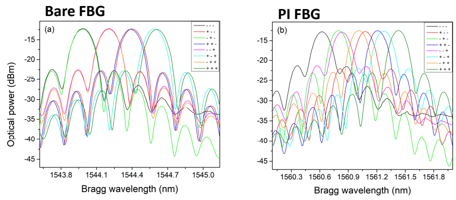
- By applying Eq. (4), all the coefficients (a) calculated, then de-normalized (S)
- All sensitivities respect to the central point calculated as well as cross interactions sensitivities, only by 8 measurements.
- Temperature sensitivity for PI FBG is slightly higher than bare FBG due to Polyimide coating.
- Strain sensitivity is in good range for both FBGs and Bare FBG is not sensitive to humidity, while PI is good transducer material for it (compare with classic measurement).
- Result of center point measurements confirms the factorial amount for S_0

Coefficients	Bare FBG	PI FBG
S_0 (nm)	1544.28	1561.03
S_t (pm/◦C)	10.18	11.18
S_h (pm/%RH)	−0.18	3.68
S_ε (pm/με)	1.16	1.14
S_{th} (pm/◦C%RH)	-0.9×10^{-2}	-3.12×10^{-2}
$S_{t\varepsilon}$ (pm/◦C με)	-6.86×10^{-4}	-9.19×10^{-4}
$S_{h\varepsilon}$ (pm/%RH με)	-3.43×10^{-5}	-1.37×10^{-3}
$S_{th\varepsilon}$ (pm/◦C%RH με)	-1.67×10^{-4}	-2.19×10^{-4}

bare FBG: 1544.29 (nm) PI FBG: 1561.027 (nm)

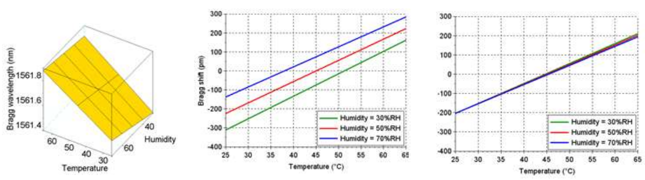
Advantages of Factorial design

- In classic experimental methods, each experimental variable is studied separately at a time
- Factorial design allows estimation of sensitivity to each factor as well as the effect of interaction between different factors.



λ_B in the PI FBG shifted with humidity modifications, while it did not in the bare FBG.

- One of the advantages of experimental design is the easy access to crosse-sensitivity coefficients.
- For e.g. temperature sensitivity slightly depends on humidity. Hence, humidity correction could be done for temperature measurements with PI FBG.



Interaction of T and %RH in stable strain for PI FBG in a)3D, b)2D, and c)bare FBG

References

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N. Safari-Yazd (nazila.safariyazd@umons.ac.be)
Electromagnetism and Telecommunication Department