Design and Simulation of Apodized π-Phase Shifted FBG as Simultaneous Sensing of Strain, Temperature, and Vibration

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***Abstract*–Fiber Bragg Gratings (FBGs) in Structural Health Monitoring (SHM) are used as an optical sensor to detect various physical phenomena to make the system more reliable and accurate. In this work, theoretical analysis and numerical simulation of an Apodized π-Phase Shifted Fiber Bragg Grating (π-PS FBG) sensor is proposed to evaluate the performance of this non-uniform FBG for simultaneous strain, temperature, and vibration sensing. Due to the accuracy and spectral characteristics of π-PS FBG, it's chosen as an optical sensor to enhance the sensibility measurements. The sensor signals designed and simulated by solving coupled mode equations using transfer matrix method in MATLAB to represent the reflected spectrum of PS FBG. As a spectral improvement purpose, the Gaussian apodization function is applied on FBG reflection spectrum to optimize spectra by supressing side lobes. Lastly, the reference FBG method calculation is used to separate vibration and temperature effects from the strain measurements.**

I. Introduction

Fiber Bragg Grating (FBG) was first presented by Hill in 1978 [1]. This fiber-optic component used as an effective monitoring tool in structural health monitoring due to the numerous advantages it offers [2]. It has a wide variety of applications for many fields such as medical, aerospace, military and so forth [3]. Simultaneous multiparameter measurements characteristic of FBG makes these optical sensors valuable to monitor the health condition of an object [2], [4]. Therefore, the promising feature of FBG is its ability in simultaneous measurement of strain, temperature, vibration, and other gauges. Among the all conventional different methods like optical, mechanical, electrical, and ultrasonic, former FBGs (electrical sensors) were used for sensing one magnitude. While increasing the number of parameters with the purpose of simultaneous measurement, were caused the complexity in both sensor design and its measurement [5], [6]. Nevertheless, the current generation of FBGs could overcome this restriction.

As follow up the recent works done in simultaneous measurement of more than one parameter, in this work, we numerically investigate the performance of one FBG under three different magnitudes: strain, temperature, and vibration. By considering the π-phase shifted FBG as an advanced optical element and using the Gaussian apodization function, sensitivity of the sensor would increase which is demonstrated as the reflection spectrum of phase shifted FBG. Moreover, due to the cross-sensitivity effect, we mathematically show the separation of strain from other parameters like temperature and vibration to have the exact measurement.

II. Model

We describe the highly sensitive optical sensor (π-PS FBG) spectral characteristics to simulate it according to the coupled mode equations using the transfer matrix method. In our designed FBG, the discontinuity of π-phase shift presented at the center of grating resulting in existence of two separate gratings. Hence, a very narrow transmission window is forming at its reflection spectrum to make the parameters measurement more precise [7], [8], [9]. In our work, the fiber length was kept constant as *25 mm* long with an effective refractive index of $n_{eff} = 1.458$, refractive index modulation change of $\delta n_{eff} = 1.1 \times 10^{-4}$, and designed wavelength of *1550 nm*. According to the mathematical model of π-phase shifted FBG spectrum, the periodic effective refractive index of the profile is defined as [10]:

$$\delta n_{eff}(z) = \overline{\delta n}_{eff}(z).\{1 + vcos[(2\pi/\Lambda).z + \phi(z)]\}. \quad (1)$$

where $\overline{\delta n}_{eff}$ is 'dc' index or apodization profile which changes over the grating length of z. v is the fringe visibility, Λ is the grating period, and $\phi(z)$ denotes the grating chirp. By solving coupled mode theory using transfer matrix method the reflection spectrum of the PS-FBG was simulated and results are shown in Fig. 1.(a). To improve sensitivity, the Gaussian apodization profile is applied to the simulated reflectivity as a filter to suppress the large and undesirable side lobes while maintaining the reflectivity high with a narrow bandwidth (Fig. 1.(b)). The apodization function is given by [9], [10]:

$$f(z) = \exp\{-4.log(2).[(z - L/2)/(s.L)]\text{^}2\}. \quad (2)$$

where L is grating length and s is an Apodized factor.

The sensing principle of FBG is based on the shift in bragg wavelength ($\lambda_B = 2n_{eff}\Lambda$ (3)) which is caused by physical

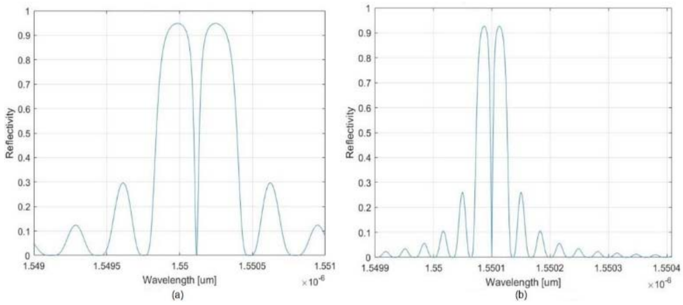

Fig. 1. (a) π-PSFBG, and (b) Apodized π-PSFBG

disturbance. The shift in bragg wavelength due to the temperature, strain, and vibration are computed as follow [4], [11], [12]:

- Temperature (ΔT): $\Delta\lambda_B = (\alpha_f + \alpha_n)\Delta T$ (4) , which thermal expansion coefficient (for Silica) is $\alpha_f = \frac{1}{\Lambda}\frac{\Delta\Lambda}{\Delta T} \approx 0.55 \times 10^{-6}\frac{1}{k}$ and thermo-optic coefficient (for Germania doped Silica) is $\alpha_n = \frac{1}{n_{eff}}\frac{\Delta n_{eff}}{\Delta T} \approx 3.0 \times 10^{-6} \sim 8.6 \times 10^{-6}\frac{1}{k}$ s.
- Strain ($\Delta\varepsilon$): $\Delta\lambda_B = \lambda_B(1 - p_e)\Delta\varepsilon$. (5) , where p_e is an effective photoelastic coefficient and it is equal to $\frac{n}{2}[p_{11} - \nu_f(p_{11} + p_{12})] \approx 0.22 \times 10^{-6}$. In this relation $p_{11} = 0.113$, $p_{12} = 0.252$, and $\nu_f = 0.16$.
- Vibration (ΔV) as a dynamic strain: $\Delta\lambda_B = \lambda_B[(1 - P_e)/E].k_e\Delta V(t,z)$. (6) that E is elasticity modulus, k_e is an elastic coefficient of fiber, and $\Delta V(t,z)$ is the vibration function with time and local functions.

To measure the sensitivity of the sensor in response to the simultaneous changes in strain, temperature, and vibration, we defined the Bragg wavelength variation as bellow:

$$\Delta\lambda_B = \lambda_B[k_\varepsilon\Delta\varepsilon + k_T\Delta T + k_V\Delta V(t,z)] + f(S,T). \quad (7)$$

where $f(S,T)$ represents as a function of strain and temperature, $k_\varepsilon = 1 - P_e$, $k_T = \alpha_f + \alpha_n$, $k_V = [(1 - P_e)/E].k_e$, are strain, temperature and vibration coefficients, respectively. Since the variation of strain and temperature affect the FBG as concurrently affected each other, so the vibration should be considered as a separate function in our simulations. Fig. 2.(a), illustrates the sensor wavelength shift modeled under different parameter changes.

To separate strain a separate stain-free FBG is considered to measure the strain from vibration-temperature sensor. Under the same condition, the strain wavelength changes can be compensated by:

$$\Delta\lambda_{(Strain)} = \Delta\lambda_{(S-T-V)} - \Delta\lambda_{(V-T)} . \quad (8)$$

Here $\Delta\lambda_{(S-T-V)}$, $\Delta\lambda_{(V-T)}$ are the wavelength shift of strain, temperature, vibration, and wavelength modification of vibration and temperature, respectively (Fig. 2.(b)).

III. Results and Discussion

In this paper the design and simulation of π-phase shifted FBG under both normal and with apodization profile are studied.

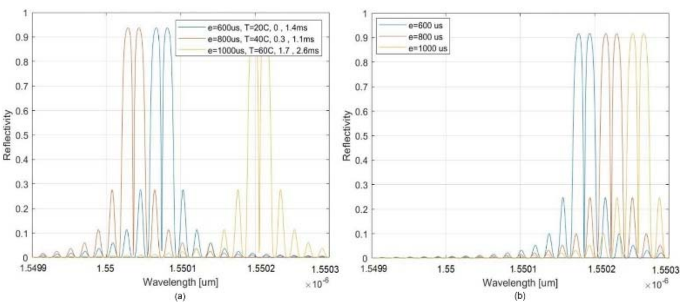

Fig. 2. (a) Apodized π-PSFBG Strain, Temperature, and Vibration Sensor and (b) Strain Compensation

From the simulation results emerges that our modeled sensor responses to three environments parameters by showing the shift in its Bragg wavelength. Comparison of π-PSFBG reflectivity, width of the signal (FWHM), and side lobes with an Apodized π-PSFBG shows that by applying the Gaussian apodization more than 92% of the side lobes suppressed, the bandwidth (FWHM) of the reflection spectrum decreased to the narrower width, although, the reflectivity almost preserved in the same height (Table 1). Thus, the improvement in spectral signal describes the prominent role of the apodization profile in enhancing the sensor sensitivity.

TABLE 1
Pi-PSFBG vs Apodization Profile Evaluation

FEATURES	REFLECTIVITY	BANDWIDTH
PS-FBG	0.9483	522.134 pm
Apodized PSFBG	0.9261	49.096 pm

Moreover, investigation of the sensor sensitivity shows that the optical element response to temperature, strain, and vibration with respect to the Bragg wavelength is linear.

Finally, it was concluded that an Apodized π-PSFBG is a good candidate to use for sensing three parameters of strain, temperature, and vibration simultaneously. Also, isolation of strain from temperature and vibration is possible.

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