MULTI-PARAMETER SENSING SYSTEM USING SAMPLED FIBER BRAGG GRATING

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Abstract: We propose a Gaussian sampled fiber Bragg grating for multi-parameter sensing system. The sampled fiber Bragg grating combines the characteristics of fiber Bragg grating and long period grating. The transfer matrix method has been used to obtain the transmission spectrum of the grating. The shifts in narrowband loss peak and broadband loss peak in the transmission spectrum have been utilized to determine the physical parameters. Results have been presented for simultaneous measurement of strain and temperature.

1. INTRODUCTION

Optical fiber sensor technology has enormous prospects in the fields of aerospace engineering, civil structures and biosensors. Fiber Bragg gratings are the preferred devices in sensor technology since they are sensitive to external physical effects but also unaffected by weathering as they are built inside the core of the fiber. Sensors based on Brillouin Scattering have the limitation of spatial resolution and also the measurement error increases for large strain difference whereas in the case of interferometric sensors, a high precision and a complicated setup is required for interrogation. In recent years, multi-parameter sensing has been an active area of research, as it minimizes the size and cost of the sensing system. Also, it would provide less complexity. Several works have been reported for simultaneous measurement of different physical parameters. A hybrid combination of Fiber Bragg Grating (FBG) and Long Period Grating (LPG) or a FBG based Fabry-Perot cavity has been proposed for multi-parameter sensor configuration [1, 2]. Sampled fiber Bragg grating or Superstructure Fiber Bragg Grating (SFBG) has drawn considerable research interest for measurement of strain, temperature and other physical parameters. An SFBG written on a dispersion shifted single mode fiber has been reported for measurement of strain and temperature [3]. A combination of SFBG and LPG has been demonstrated for simultaneous measurement of strain and temperature [4]. A high sensitivity SFBG has been reported for the simultaneous measurement of pressure and temperature [5]. The grating was fabricated by the superposition of a short period phase mask and a long period amplitude mask. However, most of the reported SFBGs are based on binary sampling functions with regions of dead space.

In our present work, we devise a Gaussian-sampled fiber Bragg grating for simultaneous measurement of strain, temperature & vibration. The grating can be easily fabricated by illuminating a phase mask with laser beam. The index modulation is created by sampling the nonlinear chirp refractive index with the Gaussian function.

2. THEORY

SFBG is generated by superimposing a periodic low spatial frequency amplitude variation on a high frequency refractive index modulation of FBG. Hence, it combines both the characteristics of FBG and LPG. Like in FBG, it causes coupling between forward propagating core mode and backward propagating core mode and results in narrowband loss peaks in the transmission spectrum. The SFBG also functions like a LPG and causes coupling between forward propagating core mode and forward propagating cladding mode resulting in broadband attenuation in the transmission spectrum. Since the co-directional coupling and counter-directional coupling exhibit different responses to environmental parameters, this bi-directional coupling property makes SFBG a very desirable sensing element for multi-parameter measurement [6].

A periodic modulation on the refractive index of the fiber can be created by illuminating a nonlinearly chirped phase mask with properly spaced Gaussian laser beam. The effective index change produced by the chirped phase mask can be written as given by [7]

$$\delta n_{eff}(z) = \overline{\delta n_{eff}}(z) \left\{ 1 + \nu \cos \left[ \frac{2\pi}{\Lambda(z)} z + \phi(z) \right] \right\}$$

(1)

where $\overline{\delta n_{eff}}(z)$ is the maximum index modulation spatially averaged over a grating period, $\nu$ is the fringe visibility of the index change, $\Lambda(z)$ is the local grating period including grating chirp and $\phi(z)$ describes the grating chirp.

The normalized index changes induced by Gaussian sampling is

$$W(z) = \sum_{n=-\infty}^{\infty} \exp \left\{ -\frac{4\ln(2)(z-np)^2}{(\text{FWHM})^2} \right\}$$

(2)
where FWHM is the full width at half maximum of the grating profile, and p is the sampling period. In the present context, nonlinear chirped grating is sampled with the Gaussian pattern. Hence, the index perturbation $\Delta n (z)$ can be written as

$$\Delta n (z) = W(z) \delta (z)$$  \hspace{1cm} (3)$$

We consider the coupled mode theory for modeling the SFBG [7]. In case of conventional FBG, the coupling between the two modes travelling in opposite direction can be written as

$$\frac{dR}{dz} = i \hat{\sigma} R(z) + i \kappa S(z)$$  \hspace{1cm} (4)$$

$$\frac{dS}{dz} = -i \hat{\sigma} S(z) - i \kappa^* S(z)$$  \hspace{1cm} (5)$$

where $R(z)$ and $S(z)$ are the amplitudes of the forward mode traveling in the $+z$ direction and of the reverse mode travelling in the opposite direction through the grating. The coordinate $z$ varies along the fiber axis from $-L/2$ to $L/2$, where $L$ is the length of the fiber grating.

The reflectivity of the grating of length ‘$L$’ can be found by assuming a forward going wave incident from $z = -\infty$ with $R(-L/2) = 1$ and no backward wave exists for $z \geq L/2$. The power coefficient can be obtained as

$$\rho = \frac{R^2(L/2)}{R^2(-L/2)}$$  \hspace{1cm} (6)$$

Different approaches exist for calculating the spectral characteristics of FBG, e.g. direct numerical integration of coupled-mode equations, the piecewise-uniform approach etc. In the present context, to model the non-uniform grating we adopt the piecewise-uniform approach, which is a transfer matrix method. In this method, the grating is divided into $M$ uniform sections and $R_i$ and $S_i$ are defined as the field amplitudes after traversing the section $i$. The propagation through each section $i$ is described by a matrix $F_i$, defined as

$$[R_i ] [S_i ] = [F_i ] [R_{i-1}] [S_{i-1}]$$  \hspace{1cm} (7)$$

For FBG, the matrix $F_i$ is given by

$$F_i = \begin{bmatrix} \cosh(\gamma \Delta z) & -i \hat{\sigma} \sinh(\gamma \Delta z) & -i \gamma \sinh(\gamma \Delta z) \\ i \gamma \sinh(\gamma \Delta z) & \cosh(\gamma \Delta z) & i \hat{\sigma} \sinh(\gamma \Delta z) \\ -i \hat{\sigma} \sinh(\gamma \Delta z) & -i \gamma \sinh(\gamma \Delta z) & \cosh(\gamma \Delta z) \end{bmatrix}$$  \hspace{1cm} (8)$$

where $\kappa$ is the “AC” coupling coefficient and $\hat{\sigma}$ is a general “DC” self-coupling coefficient and $\gamma_B$ is given by

$$\gamma_B = \sqrt{\kappa^2 - \sigma^2}$$  \hspace{1cm} (9)$$

Once all of the 2x2 matrices are known, they can be multiplied to obtain a single 2x2 matrix that defines the whole grating

$$\begin{bmatrix} R_M \\ S_M \end{bmatrix} = F_M \cdot F_{M-1} \cdot \ldots \cdot F_1 \begin{bmatrix} R(-L/2) \\ S(-L/2) \end{bmatrix}$$  \hspace{1cm} (10)$$

Here $R_M$ and $S_M$ represent the amplitudes of the forward propagating wave and the reverse propagating wave at the output at $z=L/2$. For a SFBG, we insert a phase shifted matrix $F_i^B$ between the factors $F_i$ and $F_{i+1}$ in the product in (10) for a phase shift after the $i$th section where $F_i^B$ is given by

$$F_i^B = \begin{bmatrix} \exp\left(-\frac{i \phi_i}{2}\right) & 0 \\ 0 & \exp\left(\frac{i \phi_i}{2}\right) \end{bmatrix}$$  \hspace{1cm} (11)$$

and

$$\phi_i = 2 \frac{\pi n_{eff}}{\lambda} \Delta \xi_i$$  \hspace{1cm} (12)$$

where $\Delta \xi_i$ is the separation between the two grating sections.

When external disturbances like strain and temperature are applied to the grating, the effective refractive index changes as

$$\delta n_{eff} = -n_{eff} \left[ P_{12} - u(P_{11} + P_{12}) \right] \Delta \xi / 2 + (\eta + \tilde{\xi}) \Delta T$$  \hspace{1cm} (13)$$

where $u$ represents the Poisson ratio, $P_{11}$ and $P_{12}$ are the Pockel’s coefficient components of the strain-optic tensor, $n_{eff}$ denotes the effective refractive index, $\eta$ is the thermal expansion coefficient of the fiber and $\tilde{\xi}$ denotes the thermo-optic coefficient of the fiber. $\eta$ can be neglected as compared to $\tilde{\xi}$. $\Delta \xi$ is the applied strain and $\Delta T$ is the change in temperature. It will result in shift in the Bragg wavelength and transmitted power.

The strain and temperature change can be simultaneously obtained by measuring the wavelength shift ($\Delta \lambda$) in the narrowband loss peaks and the shift in the transmitted power level ($\Delta P_T$)

$$\Delta \lambda = M_{11} \Delta \xi + M_{12} \Delta T$$  \hspace{1cm} (14)$$

$$\Delta P_T = M_{21} \Delta \xi + M_{22} \Delta T$$  \hspace{1cm} (15)$$

The coefficients $M_{11}$, $M_{12}$, $M_{21}$ and $M_{22}$ can be found by the wavelength shift and transmitted power change of the spectrum by different strain and temperatures applied to the grating.

SFBG can also sense acoustic vibrations. Transverse impingement of an acoustic wave leads to periodic microbends in the optical fiber [8]. The period of the microbends is equal to that of the
induced static vibration leading to formation of an LPG-like structure. This phenomenon modifies the co-directional coupling between the forward propagating guided-mode and forward propagating cladding-mode. The transmission spectrum of the grating is altered by the introduction of side lobes. The transmitted optical power of the side lobe can be used to measure the acoustic vibration.

3. SIMULATIONS AND RESULTS
The simulations were performed by considering the following parameters for the SFBG. The length of the grating was taken as 5cm and the average period of the chirped grating is considered as 1µm. The modeling was based on a silica fiber. The chirped grating is sampled with five Gaussian samples with the sampling peaks separated by a distance of 1cm. The effective refractive of the core is considered as 1.45 and the refractive index of the cladding as 1.44. Fig.1 represents the SFBG profile designed for the simulations. The Bragg wavelength is chosen as 1550nm. The SFBG transmission spectrum at constant temperature and zero strain is shown in Fig.2 over a wavelength range of 1430nm to 1670nm. Multiple broadband loss peaks are obtained at 1440nm, 1530nm and 1570nm. A narrowband loss peak is obtained at 1550nm. Multiple narrowband loss peaks are obtained which are spread around the 1550nm wavelength with lesser reflectivity as compared to the major narrowband loss peak.

![Fig. 1: Profile of SFBG – Gaussian Sampled Chirped Grating](image1)

![Fig. 2: Transmission spectrum of SFG at constant temperature and zero strain](image2)

Fig. 3 shows the transmission spectrum for changes in temperature at zero strain and it was observed that the wavelength of the FBG narrowband loss peak shifts towards higher wavelengths while the transmission power decreases with increase in temperature. The corresponding coefficients are $M_{11} = 0.130$ nm/°C and $M_{22} = -0.157$ dB/°C.

![Fig. 3: Variation of transmission spectrum with temperature at zero strain](image3)

Similarly, the transmission spectrum shown in Fig.4 was analyzed for changes in strain at constant temperature. It was observed that the wavelength of the FBG narrowband loss peak shifts towards higher wavelengths while the transmission power increases with increase in strain. The corresponding coefficients are $M_{11} = 1.436 \times 10^{-2}$ nm/µε and $M_{22} = 0.369 \times 10^{-2}$ dB/µε.

The variation of shift in power and wavelength vs. applied strain and temperature are shown in Fig. 5-8.

![Fig. 4: Variation of transmission spectrum with strain at constant temperature](image4)
The coefficients $M_{11}$, $M_{12}$, $M_{21}$, $M_{22}$ are utilized to determine the strain and temperature simultaneously. Work is in progress for simultaneous measurement of vibration and temperature or strain.

4. CONCLUSION
We have proposed a Gaussian sampled fiber Bragg grating for simultaneous measurement of strain and temperature. The changes in optical power of the transmission spectrum and wavelength shift of the narrowband loss peak are utilized to determine the strain and temperature. The grating will be very much useful for structural health monitoring of advanced structures.

5. REFERENCES