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An efficient method for determining transmission characteristics of superstructure fiber Bragg grating and its use for multiparameter sensing

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ABSTRACT

We propose an efficient approach for determining the transmission characteristics of periodic superstructure fiber Bragg grating (SFBG). In the analysis, the core mode and circularly symmetric cladding modes have been considered for mode coupling. The fiber Bragg grating (FBG) sections and phase shift sections of SFBG have been formulated using coupled-mode equations. The transfer matrices for both the sections have been determined using finite difference method. The modulation of transmission characteristics of SFBG under the perturbation of multiple physical parameters (e.g. strain, temperature etc.) have been investigated numerically. We have simulated the transmission characteristics of SFBG under the simultaneous application of strain & temperature in the range of 0 to 1200 $\mu\varepsilon$ and 30 to 90 °C. The results obtained show a good agreement when compared with experimental data.

1. Introduction

Over the recent years, superstructure fiber Bragg gratings have created much interest in the field of fiber optic sensors and communication. The main advantage of SFBG when used as sensors is its capability to measure simultaneously two or more physical parameters e.g. strain, temperature or any other parameters [1]. Several techniques have been reported for simultaneous measurement of two or more physical parameters, such as dual-wavelength superimposed gratings [2], hybrid FBG/LPG [3], FBG combined with EDFA [4], FBG Fabry–Perot cavity method [5], etc. However in all such techniques more than one FBG have been used. Recently fiber Bragg grating harmonics technique [6] has been reported for multi-parameter measurement, but its sensing characteristics depend on the accuracy of phase masking fabrication process. The key advantage of using SFBG as sensor is that a single SFBG can be used for measurements of two or more physical parameters.

So far, the sensing mechanism using SFBG has only been experimentally studied. As of now, there is no specific theoretical analysis for realizing the sensing technique using SFBG. Guan et. al. [1] for the first time have experimentally demonstrated how SFBG could be used for simultaneous strain and temperature sensing. Gwandu et al. [7] have reported the measurement of strain and curvature using SFBG. Temperature measurement using SFBG has been demonstrated by Fu et al. [8]. Yinquan et al. [9] have theoretically modeled SFBG, where the structure of SFBG was fabricated by dual overwriting of FBG and LPG which is different from standard SFBG fabricated with amplitude mask and phase mask technology having on–off grating structure. Another approach of modeling SFBG has been reported by Zhang et al. [11], and they have used coupled mode theory with simultaneous coupling of forward to backward guided mode and forward core to backward cladding mode.

In the present work, we propose an efficient numerical tool for determining the transmission spectra of SFBG. That technique is used to calculate the transmission spectra of SFBG when multiple physical parameters (e.g. strain and temperature) are applied simultaneously. We have analyzed the modulation of transmission spectra considering forward and backward core mode and as well as forward and backward symmetric cladding modes. In our simulation, we have considered the temperature variation and strain variation in the range of 30 to 90 °C and 0 to 1200 $\mu\varepsilon$, respectively.

2. Theoretical model

2.1. Transmission characteristics

The periodic SFBG consists of a series of grating and non-grating segments of equal lengths [10]. The grating segments act as normal

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FBG and result multiple reflection peaks in the reflection spectrum. The both segments as a whole behave as LPG and result in broadband loss peak in the transmission spectrum. In the present work, first we develop a mathematical model for determining transmission characteristics of SFBG and later we analyze the transmission characteristics of SFBG under the perturbation of physical parameters. The analysis includes the mode coupling between forward core mode and backward core mode and the core mode to both copropagating and counterpropagating cladding modes of first azimuthal order ($HE_{1\mu}$). The circularly symmetric cladding modes of odd order have similar electric field with the core mode and have a large overlap integral [12]. Hence, the coupling between them would be more efficient and has been taken into account in the present analysis. To formulate the transmission characteristics of SFBG, we first construct a matrix of an FBG section and that of a non-grating or phase shift section for a particular cladding mode. Then the matrices of the individual sections are multiplied according to the principle of Transfer Matrix Method and thus transmission or reflection coefficient has been determined.

The multimode coupled equations within an FBG section can be described as [13]:

$$\frac{dA}{dz} = i\sigma A + ik_s A_i e^{-2i\Delta\beta_s z} + ik_1 B e^{-2i\Delta\beta_1 z} + ik_i B_i e^{-2i\Delta\beta_i z} \tag{1a}$$

$R = Ae^{i(\Delta\beta_1+\Delta\beta_i+\Delta\beta_s)z}, R_i = A_i e^{i(\Delta\beta_1+\Delta\beta_i-\Delta\beta_s)z}, S = Be^{i(-\Delta\beta_1+\Delta\beta_i+\Delta\beta_s)z}$ and $S_i = B_i e^{i(\Delta\beta_1-\Delta\beta_i+\Delta\beta_s)z}$, then the coupled mode equations can be rewritten as:

$$\left.\begin{aligned}
\frac{dR}{dz} &= i(\Delta\sigma + \Delta\beta_1 + \Delta\beta_i + \Delta\beta_s)R + ik_s R_i + ik_1 S + ik_i S_i \\
\frac{dR_i}{dz} &= ik_s R + i(\Delta\beta_1 + \Delta\beta_i - \Delta\beta_s)R_i \\
\frac{dS}{dz} &= -ik_1 R - i(\Delta\sigma + \Delta\beta_1 - \Delta\beta_i - \Delta\beta_s)S \\
\frac{dS_i}{dz} &= -ik_i R + i(\Delta\beta_1 - \Delta\beta_i + \Delta\beta_s)S_i
\end{aligned}\right\} \tag{3}$$

The output amplitudes for every cladding mode of the SFBG is,

$$F.\begin{bmatrix} R(z) \\ R_i(z) \\ S(z) \\ S_i(z) \end{bmatrix} = \begin{bmatrix} R(0) \\ R_i(0) \\ S(0) \\ S_i(0) \end{bmatrix}, \quad \mathbf{F} = \mathbf{F_N}.\mathbf{F_{N-1}}...\mathbf{F_i}...\mathbf{F_1} \tag{4}$$

where F_i represents either the FBG section or phase shift section. The transfer matrices for these are formulated as follows.

To develop the transfer matrix for an uniform FBG section of length L_1 using finite difference method, a single FBG section is divided into a number of smaller subsections (M) and each having length $\Delta z = L_1/M$. It has been obtained asThe transfer matrix for the non-grating or phase shift section of length L_2 is given as

$$F_{FBG} = \begin{bmatrix} 1 - i\Delta z(\sigma + \Delta\beta_1 + \Delta\beta_i + \Delta\beta_s) & -i\Delta z k_s & -i\Delta z k_1 & -i\Delta z k_i \\ -i\Delta z k_s & 1 - i\Delta z(\Delta\beta_1 + \Delta\beta_i - \Delta\beta_s) & 0 & 0 \\ i\Delta z k_1 & 0 & 1 + i\Delta z(\sigma + \Delta\beta_1 - \Delta\beta_i - \Delta\beta_s) & 0 \\ i\Delta z k_i & 0 & 0 & 1 - iz(\Delta\beta_1 - \Delta\beta_i + \Delta\beta_s) \end{bmatrix}^M \tag{5}$$

$$\frac{dA_i}{dz} = ik_s A e^{2i\Delta\beta_s z} \tag{1b}$$

$$\frac{dB}{dz} = -ik_1 A e^{2i\Delta\beta_1 z} - ik_i A_i e^{2i\Delta\beta_i z} - i\sigma B \tag{1c}$$

$$\frac{dB_i}{dz} = -ik_i A e^{2i\Delta\beta_i z} \tag{1d}$$

where A and B are the amplitudes for the forward and backward core mode, A_i and B_i are the amplitudes for the forward and backward cladding mode, σ is a 'DC' coupling coefficient, k_1 is an 'AC' coupling coefficient, k_i is the coupling coefficient for core mode-cladding mode contra-directional coupling, and k_s is the coupling coefficient for core-clad codirectional mode coupling [14]. The Eq. (1a) describes the change in amplitude of forward core mode due to coupling from forward cladding mode and backward core and cladding modes. Similarly, the Eqs. (1b)–(1d) are formed under the corresponding couplings.

The detuning parameters are defined as follows:

$$\left.\begin{aligned}
\Delta\beta_1 &= \tfrac{1}{2}\left(2\beta_{co} - \tfrac{2\pi}{\Lambda_B}\right) \\
\Delta\beta_i &= \tfrac{1}{2}\left(\beta_{co} + \beta_{cl} - \tfrac{2\pi}{\Lambda_B}\right) \\
\Delta\beta_s &= \tfrac{1}{2}\left(\beta_{co} - \beta_{cl}^{1i} - \tfrac{2\pi}{\Lambda_s}\right)
\end{aligned}\right\} \tag{2}$$

where $\beta_k = \frac{2\pi n_{eff}^{(k)}}{\lambda}, k = (co, cl)$. β_{co} and n_{eff}^{co} denote propagation constant mode. Similarly, β_{cl} and n_{eff}^{cl} are those of LP_{01} cladding mode. β_{cl}^{1i} is the propagation constant for ith cladding mode of first azimuthal order. Λ_B is the FBG grating period and Λ_S is the LPG grating period which is equal to the sum of the length of one grating section and one phase shift section.If we assume,

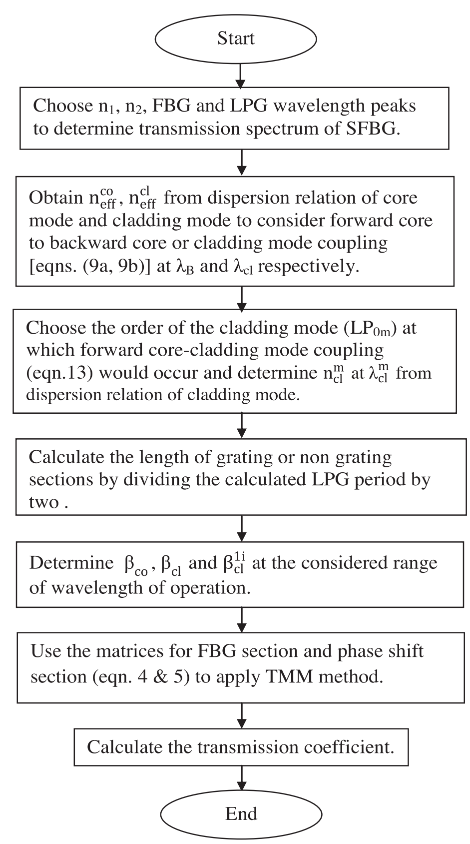

Fig. 1. A flow chart for determining the transmission characteristics of SFBG.