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Simulation method for analyzing mechanical long-period fiber gratings under high birefringence

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ABSTRACT

A simulation model based on the finite-element method (FEM) and transfer matrix method (TMM) is developed for analyzing mechanical long-period fiber gratings (MLPFGs). The anisotropic characteristics of the cross section of a fiber are obtained using FEM and the non-rectangular distribution of refractive index of the stressed area is accounted for to analyze band-rejection filtering characteristics using TMM, both of which are neglected in the conventional coupled-mode method (CMM). The overall attenuation in the entire spectral range is successfully simulated by the proposed method. The deviations of the transmittance at resonance wavelength between theoretical values and the actual conditions are 11.39 dB and 1.18 dB for CMM and FEM-TMM, respectively, for a high-birefringence case under a high applied force such as $F = 60$ N.

1. Introduction

Mechanically formed long-period fiber gratings (MLPFGs) have been widely researched and developed in optical communications and fiber-optic sensors [1–5], such as notch filters [1,2], tunable bandpass filters [3], mode converters [4], and sensors of refractive index or other parameters [5]. To date, however, most of the research on MLPFGs has been experimental investigations, and very few studies reported theoretical analyses or stimulations of MLPFGs. In 1997, Erdogan established the theoretical basis for LPFGs based on the coupled-mode theory [6,7]. There have been several studies on methods for the theoretical analysis of LPFGs, such as the integral method [8], Bloch wave theory [9], WKB method [10], and scattering theory [11].

The most recognized tool for analyzing the characteristics of an MLPFG is the coupled-mode method (CMM) [7], which will be introduced in detail in Section 2.1. However, CMM involves two approximations, which may lead to differences between simulation and experiment, especially when the fiber is under a large stress. First, although birefringence occurs when an MLPFG is formed by an external force through the photoelastic effect, the variation in the refractive-index modulation along different directions in the cross section of the fiber is not considered in CMM. Secondly, although the distribution of refractive index of the stressed area in a fiber grating is non-rectangular, it is considered to be rectangular in CMM.

In this study, to overcome the disadvantages of CMM for analyzing MLPFG characteristics, an improved simulation model was developed using the finite-element method (FEM) [12,13] and transfer matrix method (TMM). We used FEM to obtain the two-dimensional (2D) modulation of refractive index induced by birefringence. The non-rectangular distribution of refractive index of the stressed area was also taken into account, and band-rejection filtering characteristics were then analyzed using TMM to avoid approximation. Subsequently, by comparing the theoretical values of transmission and bandwidth obtained by the FEM–TMM model and CMM with experimental values, it was confirmed that the FEM–TMM method is superior, especially under a large external force.

2. Theoretical model of MLPFG

Owing to the photoelastic effect, an external force changes the refractive index of a fiber. The force applied to a single-mode fiber with a periodic interval would form an LPFG called the MLPFG. In an MLPFG, a mechanical force induces a periodical change in refractive index in both the cladding and core. It is necessary to obtain the modulation of the refractive index Δn before theoretically analyzing the band-rejection filtering characteristics of the MLPFG. Therefore, the analysis of the spectral characteristics of an MLPFG can be divided into two parts: the photoelastic part, which is associated with the determination of the modulation of refractive index, Δn,and the wave-optics part, which relates to the determination of band-rejection filtering characteristics.

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CMM uses the coupled-mode theory to solve the LPFG transmission problem. In this method, the ν-order effective refractive index (n_{eff}) of the cladding needs to be calculated first. Then, the transmission through MLPFG is calculated for a certain coupled mode. In this paper, after introducing CMM, we propose a new simulation model developed using FEM and TMM; the method uses FEM to calculate Δndue to the photoelastic effect and TMM to numerically simulate the transmission spectra of MLPFGs. The applicability of both methods will be discussed in Section 3 by analyzing and comparing simulation results with experimental data.

2.1. CMM

The first step is to calculate n_{eff}. The conventional expression describing the change of n_{eff},is as follows [14]:

$$\Delta n_{eff} \approx -\frac{n^3(1+\nu_p)}{\pi DYl}[(1+2\nu_p)p_{11}+(2\nu_p-3)p_{12}]F \tag{1}$$

where n is the initial refractive index, $\nu_p = 0.25$ is the Poisson's ratio of a normal fiber, D is the diameter of the fiber, Y is Young's modulus, l is the total length of the grating, p_{11} and p_{12} are the photoelastic coefficients, and F is the applied force. The value of Δn_{eff} calculated from Eq. (1) is an approximation because, in reality, n_{eff} is not homogeneous along different directions in the cross section of a fiber owing to the birefringence effect. Here, n_{eff} is calculated using a two-layer geometry model [15].

When the refractive index of a fiber is modulated periodically, a grating is achieved. The coupled-mode theory can be used to obtain the transmission of this grating. For an MLPFG, a fundamental linear polarization mode, LP_{01}, coupled to the ν-order cladding mode, $LP_{1\nu}$, at resonance wavelengths is described as follows [16]:

$$\frac{P_{\mathrm{cl}}^{\nu}(l)}{P_{\mathrm{co}}(0)} = \frac{sin^2[\kappa_g l\sqrt{1+\left(\frac{\delta}{\kappa_g}\right)^2}]}{1+\left(\frac{\delta}{\kappa_g}\right)^2} \tag{2}$$

where $P_{\mathrm{co}}(0)$ and $P_{\mathrm{cl}}^{\nu}(l)$ are the power of LP_{01} at the input end and power of $LP_{1\nu}$ at the output end of MLPFG, respectively. $\kappa_g = \pi\Delta n_{eff}/\lambda$ is the coupling constant, $\delta = (\beta_{\mathrm{co}}-\beta_{\mathrm{cl}}^{\nu}-\frac{2\pi}{\Lambda})/2$ is a detuning factor, and $\beta_{\mathrm{co}}$and $\beta_{\mathrm{cl}}^{\nu}$are propagation constants of the core fundamental mode, LP_{01}, and the ν-order cladding mode, $LP_{1\nu}$, respectively. Λ is the grating period. While $\delta = 0$, the equation can be converted to

$$\lambda_\nu = (n_{eff}^{co}-n_{eff}^{\nu-cl})\Lambda \tag{3}$$

Eq. (3) is known as the phase-matching condition. Here, λ_ν is the resonance wavelength, n_{eff}^{co} is the effective refractive index of the core, and $n_{eff}^{\nu-cl}$ is the ν-order effective refractive index of the cladding.

2.2. FEM–TMM

FEM is suitable for determining the distribution of the refractive index in the cross section of an MLPFG. FEM subdivides a large computational domain into smaller and simpler components known as finite elements [12,13]. Simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. The accuracy of FEM increases as the number of elements used for the division increases. It does not have a high computational cost to obtain the distribution of refractive index.

However, FEM has a very high computational cost in terms of the time and effort required to solve wave-optics problems of MLPFGs. Fortunately, wave-optics problems can be solved using TMM. TMM is based on the principle that, according to Maxwell's equations, there are simple continuity conditions for the electric field across boundaries from one medium to the next. If the field is known at the beginning of a layer, the field at the end of the layer can be derived from a simple matrix operation. A stack of layers can then be represented as a system matrix, which is the product of the individual layer matrices. The final step of the method involves the conversion of the system matrix back into the reflection and transmission coefficients.

2.2.1. Photoelastic part

The relationship between pressure and refractive index can be described as follows [17]:

$$\begin{bmatrix} n_x \\ n_y \end{bmatrix} = \begin{bmatrix} n_0 \\ n_0 \end{bmatrix} + p_{11}\begin{bmatrix} \sigma_x \\ \sigma_y \end{bmatrix} + p_{12}\begin{bmatrix} \sigma_y+\sigma_z \\ \sigma_x+\sigma_z \end{bmatrix} \tag{4}$$

where n_x and n_y are the indexes along the Cartesian axes and n_0 is the initial index of the fiber with $n_{core} = 1.4682$ and $n_{cladding} = 1.4628$; $p_{11} = 0.121$ and $p_{12} = 0.27$; and σ_x, σ_y and σ_z are the Cauchy stress tensors, which describe the mechanics tensors along the x, y and z directions, respectively.

To calculate the anisotropic index of the core and cladding, FEM is used when the grating period $\Lambda = 600\mu$m, grating length $l = 40$mm, and external force $F = 50$ N. And the external pressure is applied to the fiber from the upper along the negative direction of y axis, while the forced part is set in the middle of one period occupying a half cycle. The bottom of the fiber is set with fixed conditions. The stress distribution of one grating period is shown in Fig. 1 (for convenience of observation, the result is shown in the xz plane and yz plane, and the subgraph is shown in xy plane). Different colors represent different intensities of pressure, as shown by the color bar. In this FEM calculation, one period of MLPFG is decomposed into more than 200 thousand units and Cauchy's strain equations are used into every small component. The adjacent area is carried out by calculating the boundary conditions.

The modulation of the refractive index, Δn, along two directions, both in the core and cladding, can be calculated from Eq. (4) using the Cauchy stress tensors. For the middle point in one stressed section of the grating, the change in refractive index with pressure is shown in Fig. 2(a) and (b) for the core and cladding of the MLPFG, respectively. The terms n_x and n_y change differently as the force increases from 0 N to 50 N. Figs. 1 and 2 show that, in the x-y plane, the core and cladding of the fiber are no longer isotropic media. Therefore, we cannot simply use Eq. (1) in high-pressure conditions to describe the n_{eff} of an MLPFG, as performed in CMM.

Fig. 3 shows the refractive-index profile of one period along the z-axis of the MLPFG with the values of n_x and n_y in Fig. 2 and $F = 50$ N. A non-rectangular refractive-index profile in the stressed part of the core and cladding, which are between a rectangular and sinusoidal curve, can be observed. From Fig. 3, it can be seen that, in the z-direction, the MLPFG cannot be treated as an absolutely rectangular refractive-index profile, as in CMM, while analyzing its transmission characteristics.

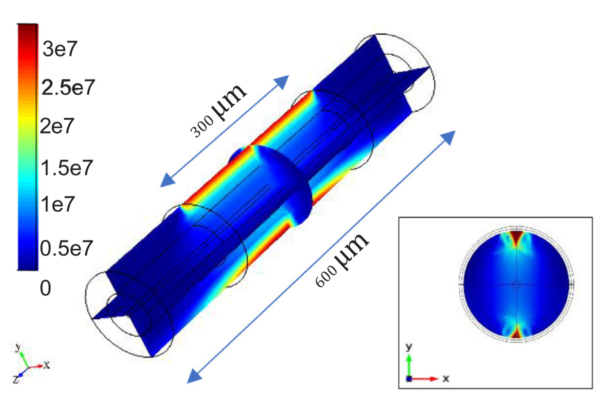

Fig. 1. Stress distribution of one period in the MLPFG.