Mode Couplings in Superstructure Fiber Bragg Gratings

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***Abstract*—The spectral characteristics of superstructure fiber Bragg gratings are analyzed numerically based on the coupled mode theory, simultaneously taking into account the counterdirectional guided mode coupling, codirectional and counterdirectional claddings mode coupling. The theoretical results were compared with experimental data and very good agreement was obtained.**

***Index Terms*—Coupled mode theory, fiber Bragg gratings, long-period gratings, mode couplings.**

I. INTRODUCTION

FIBER GRATINGS have developed into important components for many applications in telecommunications and fiber sensor systems [1]. Fiber gratings are broadly classified into two categories: fiber Bragg grating (FBG) and long-period fiber grating (LPG). The FBG typically has period less than 1 μm. It couples light from the forward guided mode to the backward guided mode and cladding modes, and thus, produces Bragg reflection and many small dips in transmission at shorter wavelength side of the Bragg wavelength. The LPG, which has period of hundreds of micrometers, couples light from the forward guided mode to the forward cladding modes, resulting in attenuation bands in the transmission spectrum. Recently, superstructure fiber Bragg grating (SFBG), which is a special type of grating fabricated by exposing the fiber to periodically modulated UV fringe pattern, has attracted much attentions [2]–[9]. SFBG is a periodically modulated FBG, and thus, introduces counterdirectional guided mode coupling at a series of regularly separated wavelengths, and so results in comb-like reflection spectrum [2]. This property of the SFBG has been fully analyzed using the coupled mode theory [3] and many applications have been demonstrated. Some examples of the applications of SFBG are comb filters for constructing tunable distributed Bragg relector (DBR) fiber lasers [4] and multiwavelength fiber lasers [5]; multichannel dispersion compensator in wavelength-division-multiplexing (WDM) systems [6], and seamless splitter/combiner in L–C band erbium-doped fiber amplifier (EDFA) [7]. On the other hand, the periodically modulated UV fringe exposure causes a periodic change in the mean index of the fiber core with a period of several hundreds micrometers, therefore, the SFBG also functions like a LPG and causes codirectional cladding modes coupling, and so results in attenuation bands in the transmission spectrum [8]. Because the codirectional coupling and counterdirectional coupling exhibit different responses to environment parameters, this bidirectional coupling property makes SFBG a very desirable sensing element for multiparameter measurement [8], [9].

In this letter, the spectral characteristics of the SFBG are analyzed numerically based on the coupled mode theory, simultaneously taking into account the counterdirectional guided mode coupling, codirectional and counterdirectional claddings mode coupling. The theoretical results are compared with the measured spectra and very good agreement was obtained. The impact of codirectional cladding modes coupling on the Bragg reflection of the guided mode is also discussed and a solution to eliminate this coupling is proposed.

II. ANALYSIS

Coupled mode theory (CMT) is often employed to analyze the optical response of dielectric optical waveguides and commonly used to study the spectral characteristics of optical fiber gratings [10], [11]. By denoting the vectors $\mathbf{A} = [a_1, a_2, \ldots a_j, \ldots a_m]^T$ and $\mathbf{B} = [b_1, b_2, \ldots b_j, \ldots b_m]^T$, where a_j and b_j are slowly varying amplitudes of the forward and backward guided/cladding electric modes, and m is the total number of selected modes, the matrix formulations of coupled mode equations can be expressed as

$$\begin{bmatrix} \mathbf{A}' \\ \mathbf{B}' \end{bmatrix} = \begin{bmatrix} \mathbf{C}^{11} & \mathbf{C}^{12} \\ \mathbf{C}^{21} & \mathbf{C}^{22} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{A} \\ \mathbf{B} \end{bmatrix} \quad (1)$$

where $\mathbf{A}'$ and $\mathbf{B}'$ represent the first order differentiate of $\mathbf{A}$ and $\mathbf{B}$ with respects to longitude coordinate z. The coupling matrix $\mathbf{C}^{\mu\nu}(\mu, \nu = 1, 2)$ are constituted by the coupling coefficients, κ_{jk} introduced by permittivity perturbations, and by the dependent factors of modes' propagation constants, which can be expressed as

$$\boldsymbol{C}_{jk}^{\mu\nu} = \kappa_{jk} \cdot \exp\left[(-1)^{\nu} \cdot i\left(\beta_j z - \frac{\pi}{2}\right) - (-1)^{\mu} i \beta_k z\right] \quad (2)$$

where β_j is propagation constant of mode $\mathbf{E}_j$ and

$$\kappa_{jk} = \frac{\omega \cdot \varepsilon_0}{4} \int_{co}\!\!\int (\mathbf{E}_k \Delta\varepsilon_r) \bullet \mathbf{E}_j^* dx dy \quad (3)$$

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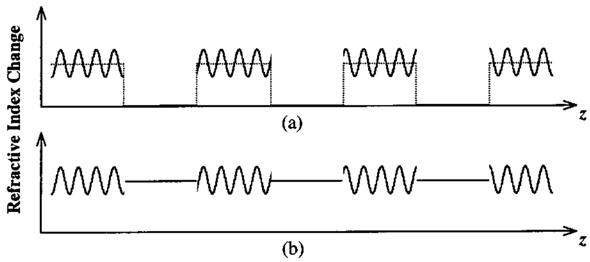

Fig. 1. Schematic diagram of the refractive index modulation of (a) conventional SFBG and (b) SFBG with the LPG component eliminated.

where ω is angular frequency, ε_0 and $\Delta\varepsilon_r$ are permittivity of free space and induced relative permittivity perturbation, respectively. If the UV induced birefringence is neglected, then the relative permittivity perturbation $\Delta\varepsilon_r$ is a scalar parameter. The coupled mode equations are usually simplified in the analysis of uniform sinusoidal gratings by assuming that it is a two-mode interaction process (i.e., only forward guided mode–backward guided mode interaction in FBGs and forward guided mode–forward cladding mode interaction in LPGs) and the grating spectra can be analyzed by fundamental matrix solutions [11], [12].

The SFBG has a special grating structure, which can be described as a series of equally spaced small FBG segments. This structure results in multiple reflection peaks in the reflection spectrum due to multiple Fourier components of its index modulation. The equally spaced FBG segments also introduce a LPG, which has dc as well as ac component equal to half of the dc component of the FBG segments [refer to Fig. 1(a)], and hence, causes attenuation bands in the transmission spectrum. Therefore, both codirectional coupling and counterdirectional coupling should be included in the theoretical analysis in order to fully understand the spectral characteristics of the SFBG. In our theoretical treatment, the coupled mode equations described in (1)–(3) are solved numerically using a direct integration method, in which forward guided mode and cladding modes and backward guided mode and cladding modes are considered simultaneously [13].

III. Results and Discussions

A 1.6-cm-long SFBG was written by scanning the fiber with a UV-beam from a 248-nm ArF excimer laser through a phase mask and an amplitude mask. The fiber used in our experiment was commercial photosensitive fiber from Fibercore Ltd (U.K.). The period of the phase mask and amplitude mask are 1.055 and 550 μm, respectively. The transmission and reflection spectra of the SFBG were measured with a broadband light source and an optical spectrum analyzer (OSA). Simulations using the theoretical approach described in the previous section were also carried out. The fiber was described by the following parameters: $n_{\rm core} = 1.4503$, $n_{\rm cladd} = 1.4441$, core diameter $=$ 5.98 μm, and cladding diameter $=$ 125 μm. The dc and ac component of the FBG segments are 7.45×10^{-4} and 2.00×10^{-4}, respectively, as determined by our calculations. In the simulations, 40 backward cladding modes and nine forward cladding modes were considered in the mode selections. Fig. 2 shows the measured and simulated transmission spectra and Fig. 3 shows the reflection spectrum. The simulated results are in very good agreement with the measured spectra.

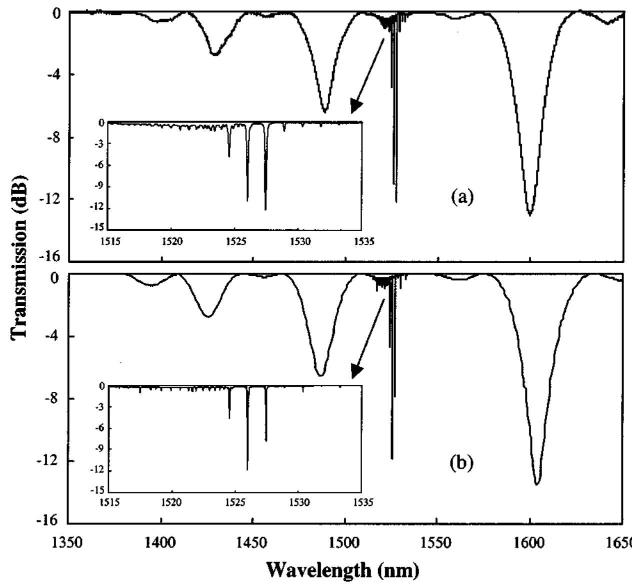

Fig. 2. Measured (a) and simulated (b) transmission spectra of an SFBG with FBG period and LPG period of 0.5275 and 550 μm, respectively. Inset shows expanded view of the transmission spectra around 1525 nm.

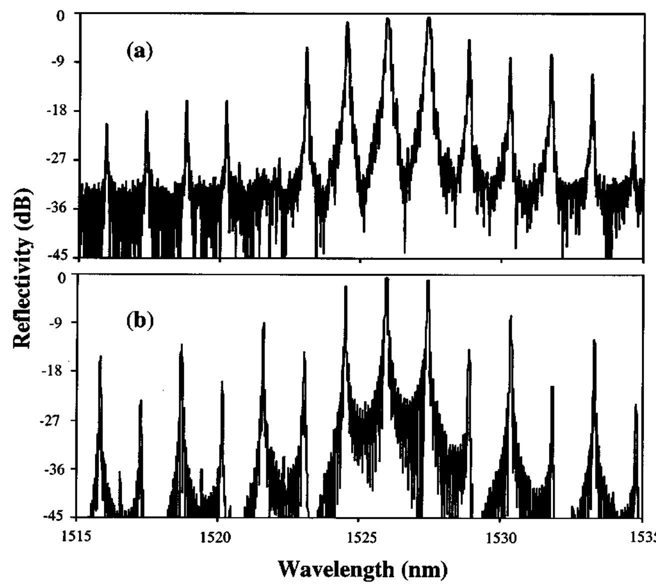

Fig. 3. Measured (a) and simulated (b) reflection spectra of the SFBG.

The SFBG possesses four LPG attenuation bands in the wavelength range 1350 $\sim$ 1650 nm, which correspond to coupling between forward LP_{01} guided mode and forward LP_{01}, LP_{03}, LP_{05}, and LP_{07} cladding modes, respectively. There are a group of narrow loss peaks around 1525 nm in the transmission spectra, which result from the counterdirectional mode coupling. The reflection peaks in Fig. 3, and the corresponding loss peaks in the insert of Fig. 2 correspond to counterdirectional guided mode coupling. Other peaks appearing at the shorter wavelength side in the insert of Fig. 2 are due to the coupling between forward guided mode and backward cladding modes. The lights propagating in backward cladding modes are quickly attenuated by scattering and bending loss, so they do not appear in the reflection spectra.

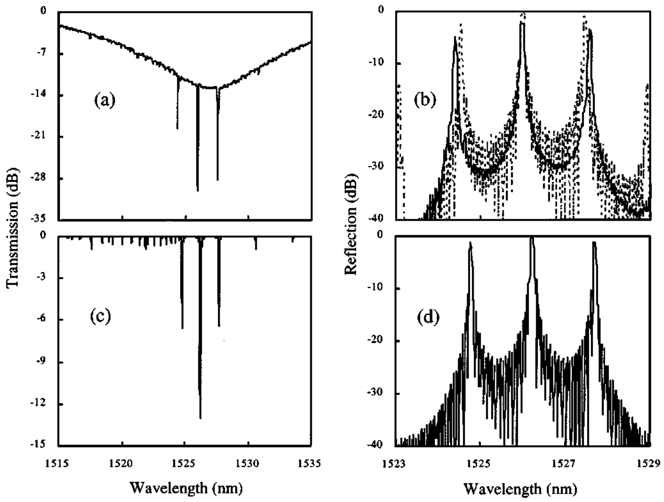

Fig. 4. (a) Simulated transmission spectra of SFBG 505, (b) simulated reflection spectra of SFBG 505 (solid line) and SFBG 550 (dashed line), (c) simulated transmission spectrum of SFBG 505 after eliminating the LPG component, and (d) simulated reflection spectrum of SFBG 505 after eliminating the LPG component.

Because codirectional cladding modes coupling and counter-directional guided mode coupling exhibit different responses to environment parameters, the bidirectional coupling characteristic of the SFBG has unique advantages for multiparameters sensing applications [8], [9]. However, it could be a drawback for SFBG when applied in communication systems, such as using as comb filters for fiber lasers and dispersion compensators for WDM channels. This is because the LPG coupling will introduce undesirable losses if the operation wavelengths (i.e., FBG resonant wavelengths) of the comb filters or dispersion compensators are located at the LPG attenuation bands. This is illustrated in Fig. 4(a) and (b). Fig. 4(a) shows the theoretical transmission spectrum of a SFBG with LPG period of 505 μm, while the other parameters are identical to the SFBG with LPG period of 550 μm (for convenience, we labeled them as "SFBG 505" and "SFBG 550," respectively, in the following discussion). The SFBG 505's reflection peaks occurred on the LPG attenuation band. Fig. 4(b) shows the theoretical reflection spectrum of SFBG 505. The theoretical spectrum of SFBG 550 is also shown for comparison. Although these two SFBGs have the same index modulation amplitude, the reflectivity of SFBG 505 is lower than that of SFBG 550 due to the LPG coupling induced losses. Such losses are not desirable for communication applications. The solution to remove these losses is to eliminate the LPG component in the SFBG. This can be achieved by exposing the previously unexposed segments of the SFBG to a uniform UV beam so that the SFBG has an index modulation as shown in Fig. 1(b). Fig. 4(c) and (d) show the respective theoretical transmission and reflection spectra of SFBG 505 after eliminating the LPG component. In this case, the LPG coupling induced losses are removed.

IV. Summary

The spectral characteristics of the SFBG are analyzed theoretically using the coupled mode theory. Three kinds of coupling effects, namely, counter directional guided mode coupling, counter directional cladding mode coupling, and codirectional cladding mode coupling are taken into account in our theoretical treatment. A good agreement between theoretical results and measured spectra are obtained. In this work, we also discussed the impact of LPG coupling on the spectral characteristics of SFBG and suggested a technique to remove the LPG feature from SFBG.

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