Step-Changed Long-Period Fiber Gratings

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***Abstract*—The spectral characteristics of a new type of long-period grating (LPG) structure, step-changed LPG, are investigated theoretically and experimentally. It is shown that the spectral profile of such gratings can be tailored by adjusting the step parameters. A good agreement between simulated results and measured spectra is obtained. This type of LPG has potential applications in gain flattening of erbium-doped fiber amplifiers.**

***Index Terms*—Band-rejection filters, gain flattening, long-period gratings, mode coupling, optical fiber filters.**

I. Introduction

LONG-PERIOD fiber gratings (LPGs) are band-rejection transmissive filters which couple light from the core of a single-mode fiber (SMF) into the cladding, thus producing attenuation bands in the fiber transmission spectrum. LPGs have many applications in both the telecommunications and fiber sensing systems [1]. In some applications, particularly for flattening the gain profile of erbium-doped fiber amplifiers (EDFA), multiple peaks and special spectral profile are required. However, the spectrum of an LPG normally has only one attenuation peak around the 1550-nm wavelength range, and so cannot meet this requirement. A reported technique for tailoring the LPG spectrum to produce multiple peaks is to introduce phase shift in an LPG [2]. Another technique to design the LPG spectrum is by cascading two independent LPGs [3]. In this case, the light coupled by the first LPG will be recoupled into the fiber core by the second LPG, leading to multipath interference, and introduces large undesirable ripples in the transmission spectrum. This problem can be eliminated by either increasing the LPG separation or bending the region between the LPGs. But these result in difficulty of realizing compact filter structure. Another solution is to utilize LPGs with different period and make the orders of the involved cladding mode in the two LPGs different with each other [4].This allows the LPGs closely spaced without recoupling interaction.

In this letter, we present a new scheme to tailor the LPG spectra by introducing a step change in the index profile of a constant pitch LPG. The step-changed LPGs were fabricated using a two-step UV-beam scanning technique with a single uniform amplitude mask. The spectral characteristics of such LPGs were predicted by numerically solving the coupled mode equations. The predicted spectra are in good agreement with the experimental results.

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II. Theoretical Analysis

The coupled mode theory with core and cladding mode descriptions of the electromagnetic fields in SMF has been applied to predict the diffraction efficiency and spectral dependence of optical fiber gratings [5], [6]. Since the counterdirectional coupling need not be considered in the long-period gratings, the coupled mode equations then can be expressed as

$$\frac{da_0}{dz} = i\kappa_{0-0}\cdot a_0 + i\sum_k \kappa_{0-k}\cdot a_k \exp\left[-i(\beta_0+\beta_k)z\right] \quad (1)$$

$$\frac{da_j}{dz} = i\kappa_{j-0}\cdot a_0 \exp\left[i(\beta_0+\beta_j)z\right] \quad (2)$$

where a_0 is the slowly varying amplitudes of the core mode, a_j $(j=1,3,5\ldots)$ is that of the cladding modes, β_0 and β_j are their propagation constants. The coupling coefficients κ_{j-k} in the above expressions are

$$\kappa_{j-k} = \frac{\omega}{4}\iint \Delta\varepsilon \mathbf{E}_k\cdot\mathbf{E}_j^* dA \quad (3)$$

where both the core and cladding electric mode $\mathbf{E}_j$ are normalized. The permittivity perturbation $\Delta\varepsilon$ is often modeled as a sinusoidal function, and the coupled mode equations have been solved analytically with the assumptions that it is a two-mode interaction process.

We model the grating index modulation as a rectangular function instead of the sinusoidal approximation commonly adopted in previous works because the LPGs are fabricated by using an amplitude mask whose period is many orders larger than the wavelength of UV light (248 nm). The index perturbations $\delta n'(z)$ of step-changed LPGs is defined as [refer to Fig. 1]

$$\delta n'(z) = \begin{cases} \gamma\cdot\delta n(z), & 0 < z > \alpha L \\ \delta n(z), & \alpha L < z > L \end{cases} \quad (4)$$

where $\delta n(z)$ is a conventional rectangular index modulation of the normal long-period gratings, γ is the step ratio $(\gamma > 1)$ which describes the amplitude of the step change, L is the grating length, and α is a normalized parameter $(0 < \alpha > 1)$ which describes the position of the step-change along the grating. Compared with conventional long-period gratings, two adjustable parameters γ and α are introduced in the step-changed long-period gratings. The following section explains how the spectral profile of the LPGs can be tailored by adjusting these two parameters.

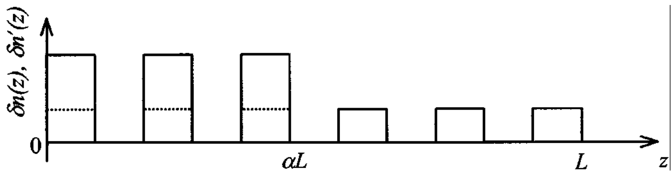

Fig. 1. Schematic diagram of the refractive index modulation of the step-changed LPG.

In general, the spectral characteristic of LPGs can be analyzed using transfer matrix based on the analytical fundamental matrix solution of (1)–(2), by considering the coupling between the core mode and the corresponding j-th $(j = 1, 3, 5 \ldots)$ cladding mode. This two-mode interaction assumption is satisfied in conventional LPGs, because its spectral separations between resonant peaks are much wider than the bandwidth of individual peaks. This method has also been extended to calculate the spectra of cascaded or phase-shifted LPGs [7], where an additional matrix representing the optical path difference or phase shift between two adjacent gratings has been inserted between two fundamental matrixes.

The step-changed LPGs can be regarded as two concatenated LPGs with zero separation, but different index modulation amplitude. For weakly step-changed LPGs $(\gamma \cong 1)$, the transfer matrix method can be directly used to analyze their spectra by multiplying two fundamental matrixes with respective grating parameters. But for strongly step-changed LPGs $(\gamma \gg 1)$, the aforementioned two-mode coupling treatment is not a good assumption. The resonant wavelength of the LPGs is very sensitive to the average index modulation, and the wavelength shift more than 80 nm during the LPG inscription was reported [8]. Therefore, for step-changed LPGs with larger γ, loss peaks and their sidelobes corresponding to different cladding modes may overlap and multimode interaction may occur. To consider these problems, the transmission spectra of this new type of LPGs were analyzed by directly employing the numerical integrations of coupled mode equations. Two cladding modes are selected together with the core mode in the numerical simulations. This approach by treating the LPGs as rectangular profile and selecting more than one cladding mode is more rigorous, and more exact results are expected than the conventional two-mode interaction treatments.

III. Results and Discussions

The LPGs were written using a 248-nm KrF excimer laser and an amplitude mask. The fibers used in the experiments were Corning SMF-28 fibers that were previously photosensitized by soaking in a hydrogen atmosphere. The period of the amplitude mask was 450 μm. The step-changed LPG was written with a two-step UV-beam scanning technique. Initially, a 2-cm normal LPG was written by exposing the hydrogen-sensitized fiber to the scanned UV-beam through the amplitude mask. Then the LPG was re-exposed by scanning the UV-beam from the beginning $(z = 0)$ of the grating to a certain position $(z = \alpha L)$, while both the amplitude mask and the fiber remained fixed. The UV-beam scanning speed during the first and second exposures and the length of the second exposure determine the step ratio γ and step location α, respectively. During the LPG inscription, both UV-beam scanning and the laser operation were controlled by a computer. The LPGs were annealed at 110°C for 6 h after they were written, then their transmission spectra were measured with a broadband light source and an optical spectrum analyzer (OSA).

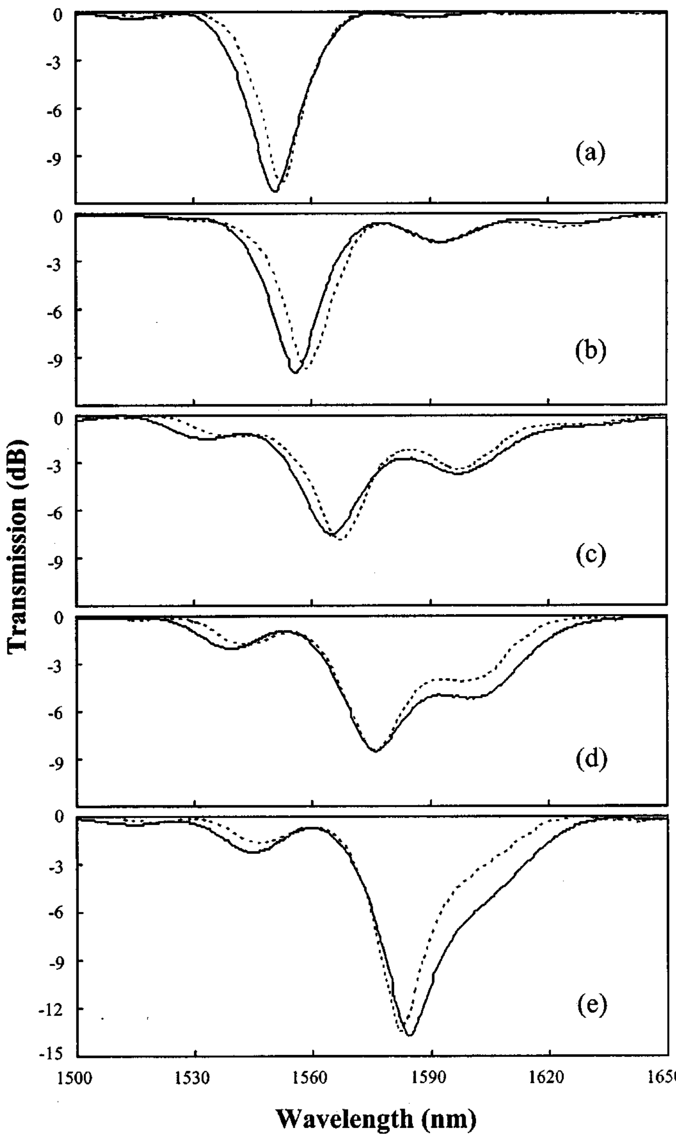

Fig. 2. Experimental (solid curve) and theoretical (dashed curve) spectra of the step-changed LPGs with $L = 2.0$ cm, $\gamma = 1.6$, (a) $\alpha = 0$, (b) $\alpha = 0.25$, (c) $\alpha = 0.4$, (d) $\alpha = 0.525$, (e) $\alpha = 0.625$.

Fig. 2 shows the spectra of a group of step-changed LPGs written with the same UV-beam scanning speed (same γ), but different exposure lengths (different α) during the second exposure. The LPG without the step change has only one attenuation peak, corresponds to LP_{07} cladding mode, in the wavelength range 1500–1650 nm. The introduction of the step-change results in the appearance of a second attenuation peak at the longer wavelength side of the original peak. The new attenuation peak increases with the length of the second exposure (i.e., α). At the same time, the original peak decreases, and the separation between the peaks decreases as well. When the length of the second exposure approaches L (i.e., $\alpha \cong 1$), two peaks will

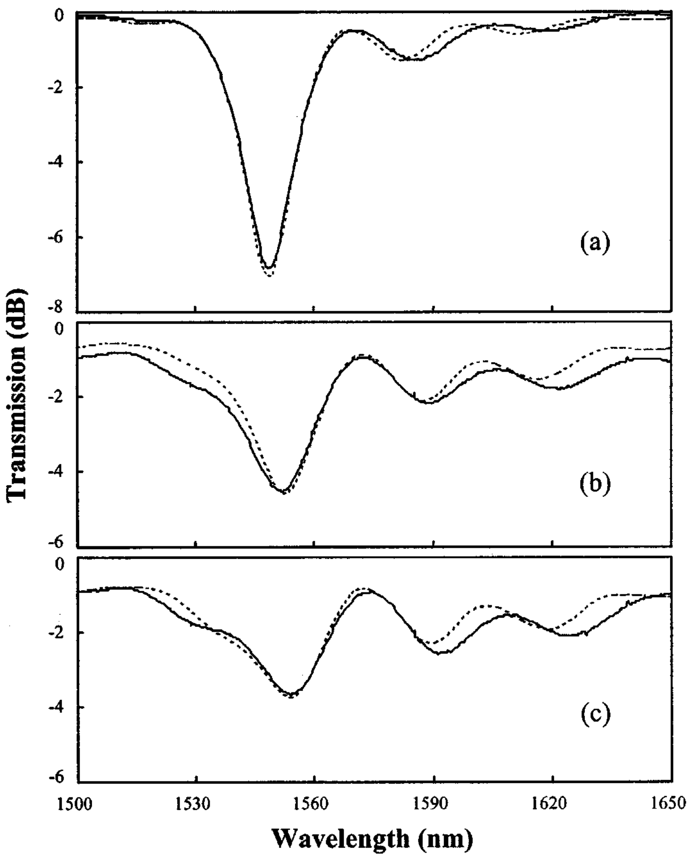

Fig. 3. Experimental (solid curve) and theoretical (dashed curve) spectra of the step-changed LPGs with $L = 2.0$ cm, $\alpha = 0.25$, (a) $\gamma = 1.6$, (b) $\gamma = 2.1$, (c) $\gamma = 2.26$.

merge into one because the LPG becomes a normal LPG with a higher index modulation. The introduction of the step-change also leads to a sidelobe at the shorter wavelength side of the original peak. The results obtained from theoretical simulation are also shown in Fig. 2 (in dashed line). It can be seen that the theoretical spectra are in very good agreement with the experimental data.

Fig. 3 shows the spectra of another group of step-changed LPGs that were written with the same exposure length (same α), but different UV-beam scanning speed (different γ) during the second exposure. With the increase of the amplitude of the step-change, a third peak appears at the larger wavelength side of the original peak. The original peak decreases with the increase of the new peaks, and the separations between the peaks stay constant. The LPGs in Figs. 2(b) and 3(a) have different index modulation amplitude although their α and γ values are the same, thus they exhibit different transmission spectra.

From both theoretical simulations and experimental results, it can be seen that the spectral profile of the LPGs can be tailored and multiple peaks can be produced by introducing a step change in the grating index profile. Since the bandwidth of the LPGs attenuation peak is inversely proportional to the grating length, the spectral shape of the step-changed LPGs can be more effectively controlled by adjusting the step parameters γ and α in combination with selecting the desired grating length L. This

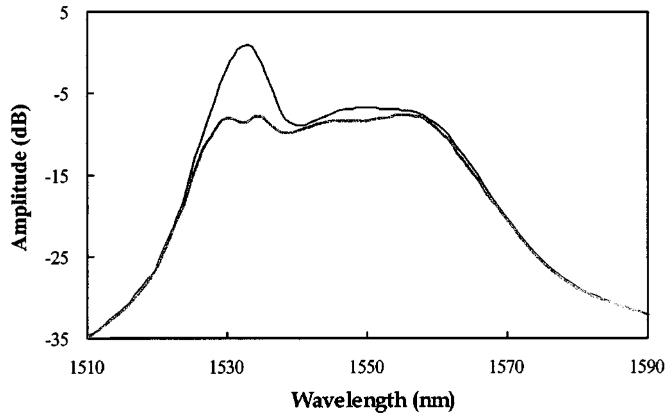

Fig. 4. Original (darker curve) and flattened (lighter curve) ASE spectrum of an EDFA.

characteristic of the step-changed LPGs has potential applications in EDFA gain flattening. This is illustrated in Fig. 4. The amplified spontaneous emission (ASE) spectrum of a 20-m-long Er-doped fiber pumped by a 980-nm laser diode is flattened to within 2 dB over 30 nm using a step-changed LPG. The parameters of the step-changed LPG used here are as follows: grating period = 455 μm, $L = 4$ cm, $\alpha = 0.25$, and $\gamma = 1.56$.

IV. Conclusion

A special LPG structure, step-changed LPG, has been investigated theoretically and experimentally. The step-changed LPGs were fabricated using a two-step UV-beam scanning technique with a single uniform amplitude mask. The spectral characteristics of this type of LPG were simulated by numerically solving the coupled-mode equations and the results obtained from the simulation shown good agreement with the measurement spectra. It has been shown that the spectral profile of such LPG can be tailored by adjusting the step parameters and this property has potential applications in EDFA gain-flattening.

References

[1] M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, T. Erdogan, and J. E. Sipe, "Long-period fiber gratings as band-rejection filter," *J. Lightwave Technol.*, vol. 14, pp. 58–65, Jan. 1996.

[2] J. R. Qian and H. F. Chen, "Gain flattening fiber filters using phase-shifted long period fiber gratings," *Electron. Lett.*, vol. 34, pp. 1132–1133, May 1998.

[3] A. M. Vengsarkar, J. R. Pedrazzanni, J. B. Judkins, P. J. Lemaire, N. S. Bergano, and C. R. Davidson, "Long-period fiber-grating-based gain equalizers," *Opt. Lett.*, vol. 21, pp. 336–338, Mar. 1996.

[4] M. Harumolo, M. Shigehara, M. Kakui, H. Kananori, and M. Nishimura, "Compact long-period grating module with multi-attenuation peaks," *Electron. Lett.*, vol. 36, pp. 512–513, Mar. 1998.

[5] T. Erdogan, "Cladding-mode resonance in short- and long-period grating filters," *J. Opt. Soc. Amer. A—Optics Image Science and Vision*, vol. 14, pp. 1760–1773, Aug. 1997.

[6] ——, "Fiber grating spectra," *J. Lightwave Technol.*, vol. 15, pp. 1277–1294, Aug. 1997.

[7] B. H. Lee, Y.-J. Kim, Y. Chung, W.-T. Han, and U.-C. Paek, "Analytic solution for cascaded long period fiber gratings," *IEICE Trans. Communications*, vol. E84-B, pp. 1247–1254, May 2001.

[8] B. O. Guan, H. Y. Tam, H. L. W. Chan, C. L. Choy, and M. S. Demokan, "Growth characteristics of long-period gratings in hydrogen-loaded fiber during and after 193 nm UV inscription," *Meas. Sci. Technol.*, vol. 12, pp. 818–823, July 2001.