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Designing optimal long-period fiber gratings with the overlapped Gaussian-apodization method for flattening EDFA gain spectra

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Abstract

A new and effective optimization approach to the inverse design problems of complex long-period fiber grating (LPG) filters was developed in the present study. The proposed synthesis method was based on the overlapped Gaussian-apodization method and the evolutionary optimization algorithm which can efficiently search for optimal solutions and simultaneously take into account various experimental requirements for the fabrication of the designed filters. To verify the effectiveness of the proposed method, a LPG filter for flattening EDFA gain spectra was designed. Compared to the existing results from discrete layer-peeling (DLP) inverse scattering algorithms, an LPG filter with adaptive grating lengths and much simpler, smoother, and less complicated coupling coefficient profiles for taking the practical fabrication conditions for gain flattening into account, was used in the proposed method. Simulation results confirm that optimal solutions of an LPG filter design are suitable for practical fabrication.

Keywords: Long-period fiber gratings; Grating synthesis; Optimization method; EDFA gain flattening

1. Introduction

Long-period fiber gratings (LPGs), in which the guided core mode is coupled to one or several forward propagating cladding modes, have been demonstrated to be useful in applications like band-rejection filters, high sensitivity sensors, mode converters, and especially erbium-doped fiber amplifier (EDFA) gain flattening filters in order to achieve uniform output power and similar signal-noise ratios. LPGs are good devices for EDFA gain flattening filters due to their low insertion loss, compatibility to optical fibers, and compactness [1]. Various design schemes of LPG devices have been proposed to equalize the gain spectrum of an EDFA [2–5]. However, previously proposed gain-flattening systems based on phase shift were two or multiple different LPGs scraped together or especially arranged in order to match the spectral shaping which limits the flexibility of the spectrum-tailoring of filter design, fabrication and packaging. According to the literature, theoretically inverse design the grating-assisted codirectional couplers (GACCs) and LPGs based on the discrete layer-peeling (DLP) inverse scattering algorithm can be used to find the coupling coefficient corresponding to a given spectral response [6]. Although, theoretical LPGs for the gain flattening of EDFAs with the required spectral shaping can be inversely synthesized by using the DLP algorithm. In practice, there are still a number of disadvantages in designing such a high standard LPG filter using this method. These include: the required grating length is typically long and the spatial grating profiles (including amplitude and phase) are complicated, even though the DLP method is exact. Because of these disadvantages, the practical application of the devices is severely limited. To overcome the difficulties mentioned above, a single period, 4 cm-long LPG with proper design can achieve good gain flattening for the entire EDFA band as proposed in a previous paper [7]. Although LPGs are easier to fabricate than FBGs, the coupling coefficient profiles of the previous devices in [7], with their coupling coefficient profiles discretized into 20 uniform sections, are still not

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easy and convenient enough for practical fabrication when using the UV-beam-scanning exposure system with the amplitude-mask writing technology or other alternative UV writing techniques [8,9] utilized in the laboratory. This is mainly because the UV beam output from the exposure laser used for fiber grating writing is normally a Gaussian profile with a certain width, which is not suitable for writing the coupling coefficients with uniformly leveled profiles. To solve this difficulty, in this study, a new approach is proposed for designing fiber grating filters by using an overlapped Gaussian-apodization method together with an optimization approach based on the evolutionary programming (EP) optimization method using probabilistic search algorithms gleaned from the organic evolution process.

From the simulation results, an adaptive grating length and much simpler and smoother coupling coefficient profiles, while taking into account the practical fabrication conditions for gain flattening of C-band EDFA, can be obtained with the proposed method. The results also confirm that optimal solutions for the Overlapped Gaussian-apodization LPG (OGA-LPG) filters, suitable for practical fabrication by using the UV-beam-scanning exposure system with amplitude-mask writing technology, can be obtained.

2. Optimization method for designing OGA-LPG

It is well known that in the practical sequential UV writing process for fiber gratings, a Gaussian beam with a suitable beam width is first chosen and then the translation length per step is adjusted in such a way that the adjacent exposure segments are overlapped in order to get a smoother coupling coefficient profile. In addition, the abrupt phase changes between adjacent segments can be smoothed out by overlap-averaging [10]. The power of the UV Gaussian beam and the fitting curve are shown in Fig. 1. Based on the above solution, every Gaussian beam can be assumed and described as below:

$$G_j(z) = A_j \cdot \exp\left\{-4\ln 2 \cdot \left[\frac{(z - (\sum_1^j z_j))^2}{(\mathrm{FWHM})^2}\right]\right\} \tag{1}$$

Here j is the number of the jth Gaussian function, A_j is the amplitude of the jth Gaussian beam, FWHM is the full width half maximum of the Gaussian function, z_j is the length between the peak positions of the jth Gaussian beam and the $(j-1)$th Gaussian beam (see Fig. 2). The solution algorithm synthesizes the coupling coefficient $(\kappa(z))$ of the OGA-LPG filters by adjusting the peak amplitude of the jth Gaussian beam (A_j) and the peak positions (z_j) between the Gaussian beams. The envelope of coupling coefficient $(\kappa(z))$ can be described in the following:

$$\kappa(z) = \sum_{j=1}^{m} G_j(z) \tag{2}$$

Here m is the total number of overlapped Gaussian beams. A set of optimal solutions $(\vec{A}_j, \vec{Z}_j)$ of the Gaussian functions for target performance was calculated by using the EP optimization algorithm which was presented in a previous paper [7]. During the optimization procedure, the coupling coefficient sorted the real and the imaginary part for satisfying the given OGA-LPG filter in order to tailor the desired spectral response. It was started by using a set of random numbers of $\vec{A}_{R,j}, \vec{Z}_{R,j}$ of the Gaussian apodized functions for the real part $(\kappa_R(z))$ and another set of random numbers $(\vec{A}_{I,j}, \vec{Z}_{I,j})$ for the imaginary part $(\kappa_I(z))$ evolving into a complex coupling coefficient profile: $\kappa(z) = \kappa_R(z) + i\kappa_I(z)$ to meet the target performance of the filter design. Here $\kappa_R(z)$ and $\kappa_I(z)$ were, respectively, the real part and imaginary part of the evolving envelopes.

The synthesized OGA-LPG transmission spectrum can be directly calculated by solving the well-known coupled mode equations:

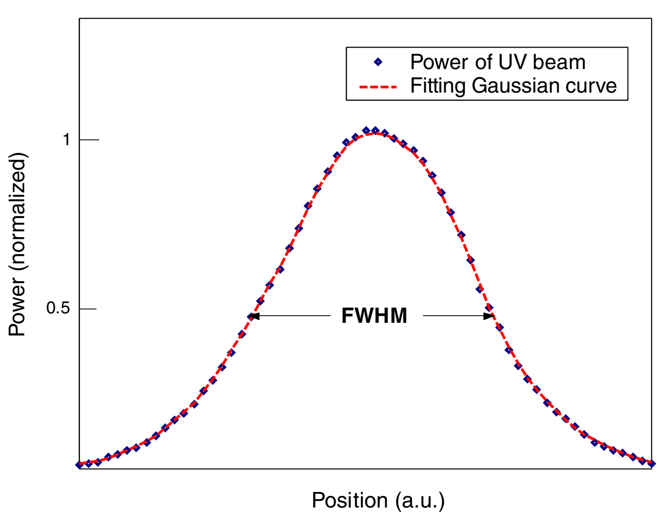

Fig. 1. The measured power of the UV beam from the exposure laser and the fitting Gaussian-curve.

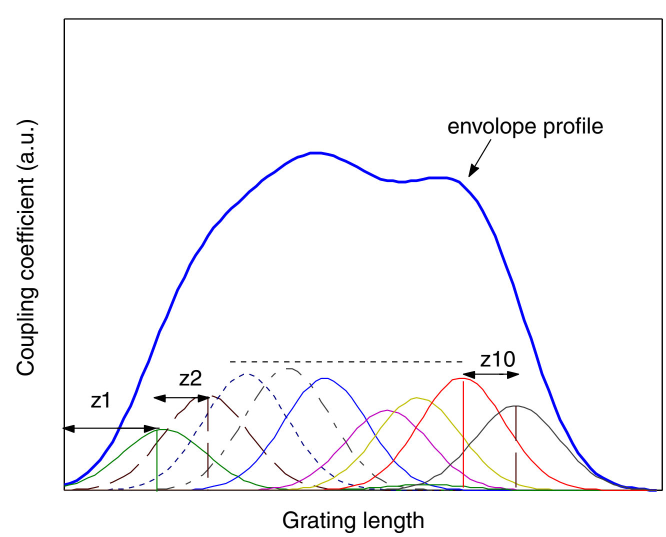

Fig. 2. The resultant coupling coefficient profile obtained by the overlapped Gaussian functions.

$$\frac{dA^{co}(z)}{dz} = i\delta A^{co}(z) + i\kappa(z)A^{cl}(z) \quad (3)$$

$$\frac{dA^{cl}(z)}{dz} = -i\delta A^{cl}(z) + i\kappa^{*}(z)A^{co}(z) \quad (4)$$

Here $A^{co}(z)$ and $A^{cl}(z)$ represent the core and the cladding modes respectively, $\delta = (1/2)[\beta^{co} - \beta^{cl} - 2\pi\ /\Lambda] = \pi\Delta n_{eff}(1/\lambda - 1/\lambda_{D})$ is the detuning parameter, Λ is the grating period, $\lambda_D = \Delta n_{eff} \cdot \Lambda$ is the designed wavelength, Δn_{eff} is the difference of the effective indices for the core and cladding modes, β^{co} and β^{cl} are the propagation constants, and $\kappa(z) = \eta\pi\Delta n(z)/\lambda_D$ is the designed coupling coefficient distribution function with $\Delta n(z)$ being the envelope function of the grating index modulation and η the overlapping factor. If only the coupling between two modes (core mode and one cladding mode) in an LPG is considered, the corresponding coupled mode equations can be solved by multiplying all of the fundamental 2×2 matrix together for efficiently calculating the synthesized spectra [11].

3. Design results and discussion

To demonstrate the effectiveness of the proposed synthesis algorithm for the OGA-LPG filter, a practical design example of EDFA gain flattening filter is presented in this section. The EDFA has emerged as a major enabler in the development of fiber-optics networks. For applications in dense wavelength division multiplexing (DWDM) systems, it is desirable to have a flat optical gain curve to ensure that the power of every channel remains roughly equal even after long distance propagation and cascading amplifications. One way to flatten the EDFA gain spectrum is by using a gain-flattening filter. Since the LPG can be used as a wavelength dependent loss element with very low back reflection, it is quite suitable for this application.

In the following design example, the number of the overlapped Gaussian beam is set to be $m = 10$, the effective propagation index difference between the core and cladding modes is $\Delta n_{eff} = 10^{-2}$ and the resonance wavelength λ_D for the OGA-LPG filter is set at 1531.1 nm, yielding a grating period $\Lambda = 153.1$ μm. Fig. 3(a) shows the target spectrum and the calculated spectrum from the designed OGA-LPG with grating length 4 cm and the FWHM of every single beam 4 mm. Fig. 3(b) shows the designed coupling function of the synthesized 4 cm-OGA-LPG for gain flattening of EDFA and the amplitude and phase profiles of the coupling coefficient across the grating also are shown in this figure. Fig. 3(c) and (d) show the EDFA gain spectrum before and after flattening with the designed 4 cm-OGA-LPG filter. In Fig. 3(d) the studied spectrum can be flattened to less than ±0.45 dB variation within the entire C-band.

Fig. 4 (a)–(d) shows the results of the same designed case with different parameters of OGA-LPG. The designed grating length is set at 6 cm and the FWHM of every single beam is 6 mm. Especially in Fig. 4(d), it can be seen that the ripple deviation in the flattened wavelength region is less than ±0.23 dB within a 30 nm bandwidth and below a ±0.5 dB variation within the 38 nm bandwidth. The typical evolution curves of the calculated average error (total error/the number of spectral points) of the above two designed cases on the proposed method are shown in Fig. 5. In this study, optimization algorithm is implemented using the Matlab5.3 program environment and executed on a Pentium IV personal computer.

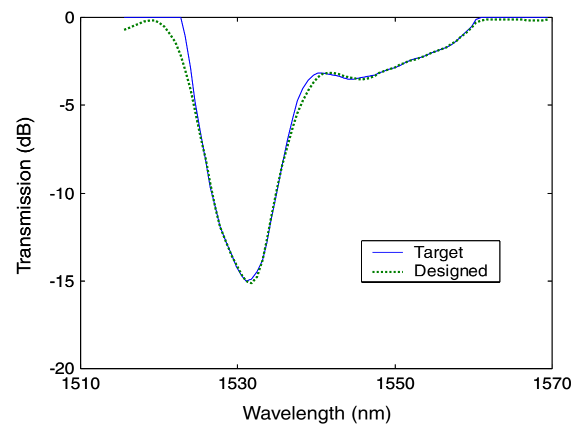

Fig. 3a. Target and designed transmission spectra of the EDFA gain flattening filter with the designed 4 cm-OGA-LPG filter.

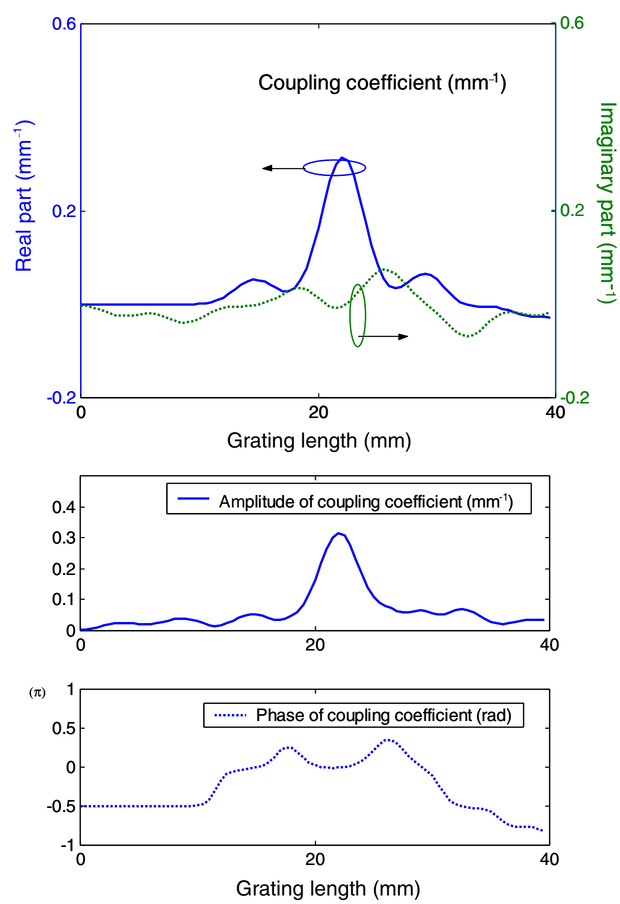

Fig. 3b. Designed coupling coefficient profile of the OGA-LPG filter with grating length 4 cm, FWHM 4 mm.

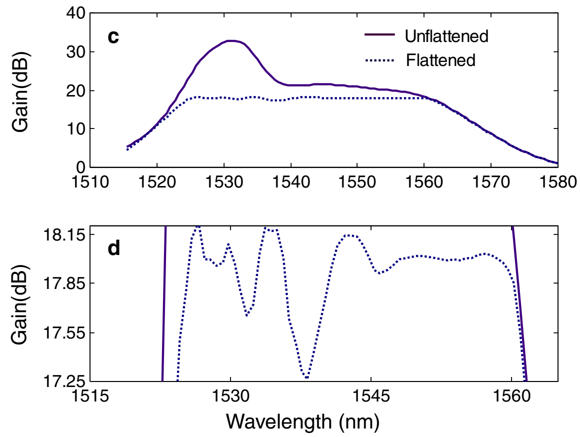

Fig. 3. (c) Flattened gain-profile (dotted line) and un-flattened gain curve of the measured EDFA (solid line). (d) Ripple deviation in the flattened wavelength region.

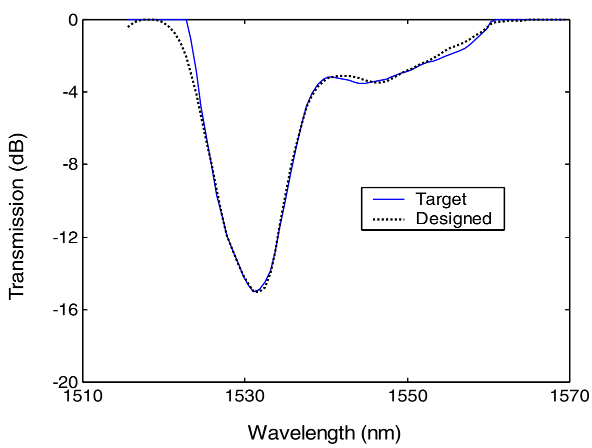

Fig. 4a. Target and designed transmission spectra of the EDFA gain flattening filter with the designed 6 cm-OGA-LPG filter.

The above design example demonstrates that multiple solutions for almost the same results can be obtained by using the proposed method.

In Fig. 6 an example is given of a simple tolerance analysis of the designed 6 cm-OGA-LPG filter when fabricating the EDFA gain flattening filter. Random phase error equivalent to a maximum of ±10 μm random position error is introduced between adjacent segments during fabrication. The simulated transmission coefficient variation shown in the figure is less than 0.3 dB. As can be seen in Fig. 6, there is no difference between the spectra of the designed OGA-LPGs when using exact and ±10 μm random position error fabrication processes. This simple analysis provides an estimate of the required fabrication precision of the designed OGA-LPG devices. The results show that the maximum phase-shift error tolerance is much larger (±10 μm) when compared to the single-period multi-phase-shifted LPGs (±50 nm) of the previously designed LPG filter for EDFA gain flattening [12]. It should therefore also be quite feasible to actually

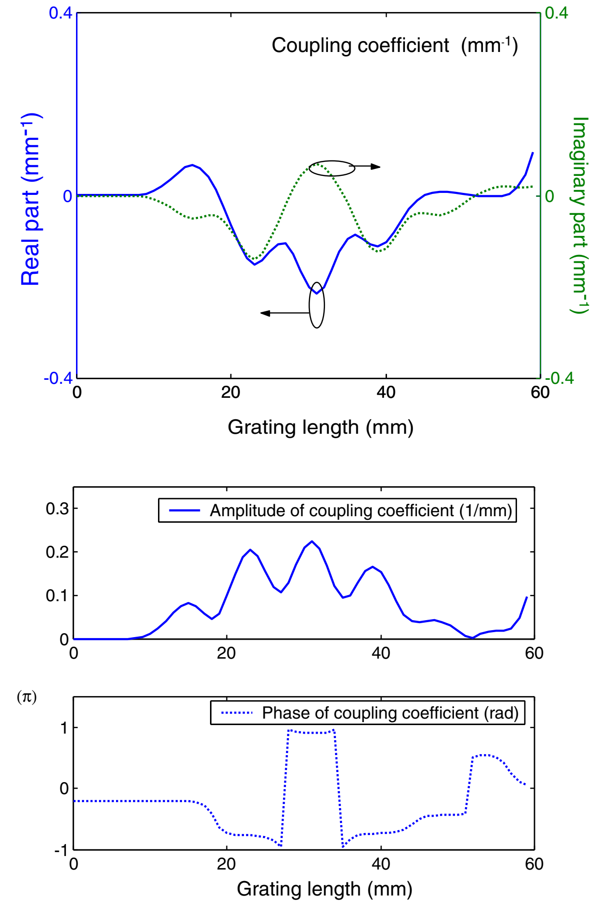

Fig. 4b. Designed coupling coefficient profile of the OGA-LPG filter with grating length 6 cm, FWHM 6 mm.

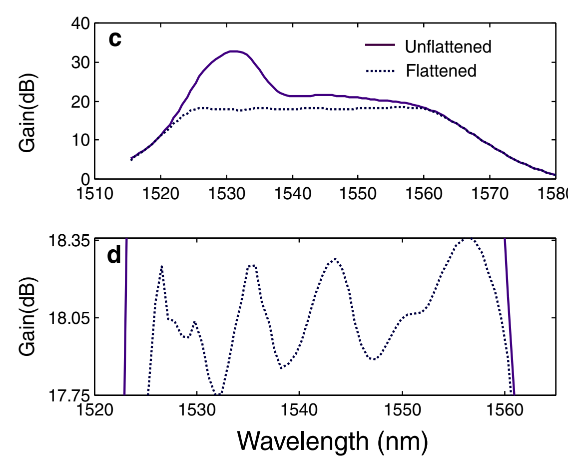

Fig. 4. (c) Flattened gain-profile (dotted line) and un-flattened gain curve of the measured EDFA (solid line). (d) Ripple deviation in the flattened wavelength region.

fabricate the designed OGA-LPG devices presented in this paper. It should be emphasized that, from the designed results, multiple solutions of OGA-LPGs for the entire C-band EDFA gain flattening were obtained. These designed effects can provide an adaptive optimization

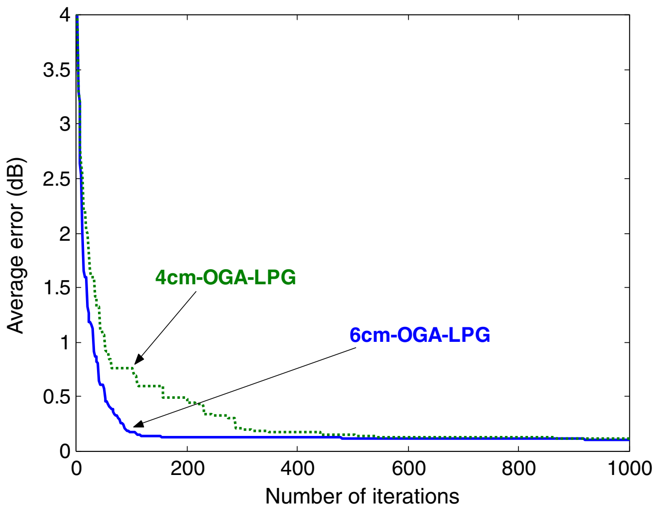

Fig. 5. Average error evolution curves for the designed OGA-LPGs.

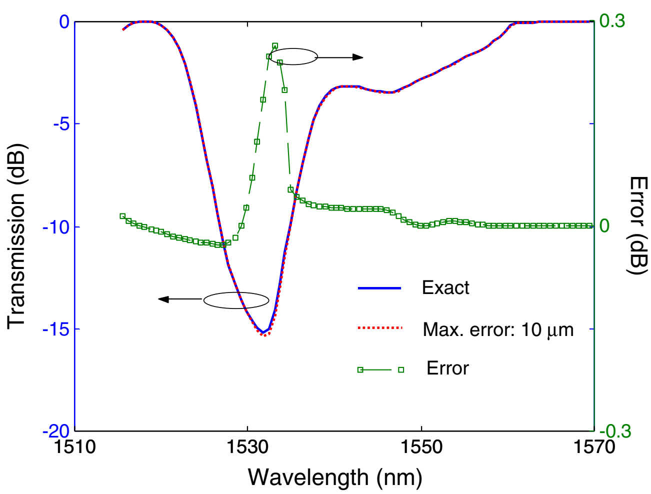

Fig. 6. Spectra with ±10 μm random position errors between adjacent segments. Dash-squared line represents errors.

solution to co-operate the experimental requirements with UV exposure parameters. In addition, during the optimization process, the synthesized maximum amplitude of the coupling coefficient was kept at 1 mm^{-1} (index modulation $\eta\Delta n \sim 5 \times 10^{-4}$) so that the designed results could be implemented with the available photosensitive fibers.

4. Conclusion

In this paper, we have reported on an effective OGA-LPG synthesis method based on the EP optimization and the overlapped Gaussian-apodization methods making it possible to take into account the experimental requirements and to constrain and adjust the designed coupling constant for the commercially available photosensitive fibers. Based on the simulation results, it was found that a smoother and less complicated coupling coefficient can be obtained by using the proposed method compared to DLP inverse scattering methods. A simple tolerance analysis for practical implementation has shown that it should be quite feasible to meet the required accuracy with the simply equipped exposure system. From the results, it is believed that the proposed method is an attractive and efficient way of optimally designing complicated fiber grating devices for practical applications and that the designed OGA-LPG also is a practical LPG structure for the gain flattening of EDFAs.

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References

[1] A.M. Vengsarkar, J.R. Pedrazzani, J.B. Judkins, P.J. Lemaire, N.S. Bergano, C.R. Davidson, Opt. Lett. 21 (1996) 336.
[2] M. Harumoto, M. Shigehara, H. Suganuma, J. Lightwave Technol. 20 (2002) 1027.
[3] J.R. Qian, H.F. Chen, Electron. Lett. 34 (1998) 1132.
[4] M.G. Xu, R. Maaskant, M.M. Ohn, A.T. Alavie, Electron. Lett. 33 (1997) 1893.
[5] A.P. Zhang, X.W. Chen, Z.G. Guan, S.L. He, H.Y. Tam, Y.H. Chung, IEEE Photonic Tech. Lett. 17 (2005) 121.
[6] J.K. Brenne, J. Skaar, J. Lightwave Technol. 21 (2003) 254.
[7] C.L. Lee, Y. Lai, IEEE Photonic Tech. Lett. 14 (2002) 1557.
[8] K.P. Chuang, Y. Lai, L.G. Sheu, IEEE Photonic Tech. Lett. 16 (2004) 834.
[9] I. Petermann, B. Sahlgren, S. Helmfrid, A.T. Friberg, P.-Y. Fonjallaz, Appl. Opt. 41 (2002) 1051.
[10] L.G. Sheu, K.P. Chuang, Y. Lai, IEEE Photonic Tech. Lett. 15 (2003) 939.
[11] T. Erdogan, J. Lightwave Technol. 15 (1997) 1277.
[12] C.L. Lee, Y. Lai, Fiber Integrated Opt. 23 (2004) 249.