Cladding-mode-assisted recouplings in concatenated long-period and fiber Bragg gratings

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We investigate new types of mode recouplings in a concatenated grating structure comprising a long-period grating and a fiber Bragg grating. It is demonstrated that the light coupled out to the cladding mode by one of these gratings can be recoupled back to the guided mode by the other grating. Theoretical analysis based on the coupled-mode theory is presented, together with experimental results. © 2002 Optical Society of America

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Optical fiber gratings have become one of the most important components in optical fiber sensing and fiber communications systems.[1,2] Fiber gratings are broadly classified into fiber Bragg gratings (FBGs) and long-period gratings (LPGs). The period of FBGs is approximately half a micrometer, which introduces a fast spatial frequency in an optical fiber. From the conventional coupled-mode theory, the guided mode whose propagation constant is half of this spatial frequency will be coupled to the corresponding backward mode.[3] Contrary to the contradirectional coupling in FBGs, LPGs induce codirectional coupling in optical fiber. The period of a LPG is several hundred micrometers, which introduces a slower spatial frequency than in FBGs. The guided mode will be coupled to the cladding modes when the difference of their propagation constants is equal to the corresponding spatial frequency. Recently, grating structures based on LPGs, FBGs, and their combinations attracted intense attention because of their novel mode coupling behaviors. Chirped sampled gratings have been proposed as a multichannel dispersion compensators, in which the multiple reflection peaks result from the different orders of grating Fourier components.[4] Some interesting mode couplings in the LPG pair were also observed, in which the light coupled to the cladding modes by the first LPG was recoupled to the fiber core by the second LPG and resulted in multipath interference fringes in the transmission spectrum.[5]

In this Letter we report a new type of mode coupling in a concatenated grating structure that consists of a weak LPG and a strong FBG. This grating device may have applications in spectrum-tunable fiber-optic components and multiparameter sensing systems. The previously proposed hybrid sensing scheme, which comprises one LPG and two FBGs, uses the conventional spectral characteristics of the gratings,[6] whereas the special reflection spectrum presented in this Letter results from cladding-mode-assisted recouplings in a LPG and another FBG concatenated grating structure. Figure 1 shows the proposed concatenated grating structure and two different types of mode recoupling mechanism. In type I recoupling (Fig. 1a), the guided light coupled to the backward cladding mode by the FBG is recoupled to the guided mode by the LPG. In type II recoupling (Fig. 1b), the guided light coupled from the core to the cladding mode by the LPG is recoupled to the backward guided mode by the FBG. It is important that the light propagate through the LPG before the FBG for these recoupling mechanisms to occur.

For a typical three-layer step-index single-mode fiber, its electric field can be considered a superposition of the fundamental guided and cladding modes.[3] If β_0 is denoted as the propagation constant of the fundamental guided mode and β_j ($j = 1, 2, 3, \ldots$) is the different-order cladding modes, the phase-matching condition for the FBG with a period of Λ_B and the LPG with a period of Λ_L are $\beta_0 + \beta_j = 2\pi/\Lambda_B$ ($j = 0, 1, \ldots$) and $\beta_0 - \beta_j = 2\pi/\Lambda_L$ ($j = 1, 3, \ldots$), respectively. By use of the relation $\beta_j = 2\pi n_{\mathrm{eff}}^{(j)}/\lambda$ ($j = 0, 1, 2, \ldots$), where $n_{\mathrm{eff}}^{(j)}$ is the effective index of the corresponding mode, the phase-matching conditions can be rewritten as

$$\lambda_B^{(j)} = [n_{\mathrm{eff}}^{(0)} + n_{\mathrm{eff}}^{(j)}]\Lambda_B\,, \tag{1a}$$

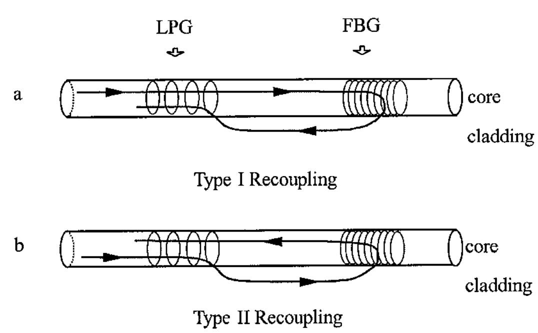

Fig. 1. Recouplings of the coupled light to the backward guided mode in the concatenated LPG and FBG. a, backward cladding-mode-assisted recoupling; b, forward cladding-mode-assisted recoupling.

$$\lambda_L^{(j)} = [n_{\text{eff}}^{(0)} - n_{\text{eff}}^{(j)}]\Lambda_L \,, \qquad (1\text{b})$$

where $\lambda_B^{(j)}$ is the resonant wavelength of the contradirectional coupling in the FBG and $\lambda_L^{(j)}$ is the resonant wavelength of the codirectional coupling in the LPG. If the difference of corresponding effective indices in the LPG and FBG is neglected, and using Eqs. (1a) and (1b), the wavelengths of the two types of recoupling can be determined as

$$\lambda_{\text{I,II}} = \lambda_B\left(1 - \frac{\Lambda_B}{\Lambda_L + \Lambda_B}\right), \qquad (2)$$

where $\lambda_B = 2n_{\text{eff}}^{(0)}\Lambda_B$ is the Bragg wavelength of the FBG. The index modulations of the LPG and the FBG are often different from each other as a result of different fabrication conditions. When we consider the narrow resonant bandwidth of the FBG and the much broader resonant bandwidth of the LPG, only one cladding mode can satisfy the phase-matching conditions and couple with the guided mode in the LPG at the wavelength at which the Bragg interactions between guided and cladding modes in the FBG take place. Then, wavelength $\lambda_{\text{I,II}}$ is determined by the FBG [Eq. (1a)], but the order of the corresponding cladding mode, j, is determined by the LPG [Eq. (1b)].

The optical power of the reflected light in such a grating structure is determined by both contradimensional and codirectional couplings between the guided mode and corresponding cladding mode in the FBG and LPG. If the loss of the LPG is considered, the resulting reflectivity, $\tilde{R}_B$, at Bragg wavelength λ_B of the FBG can be written as

$$\tilde{R}_B = [T_L^{(j)}]^2 R_B^{(0)} \,, \qquad (3)$$

where $T_L^{(j)}$ ($j = 1, 2, \ldots$) denotes the transmission of the guided mode of the LPG at the wavelength at which the coupling with the jth cladding mode takes place and $R_B^{(j)}$ ($j = 0, 1, \ldots$) denotes the reflectivity corresponding to the coupling from the guided mode to the jth guided or cladding mode in the FBG. By considering the light of the type I and type II recouplings as propagating in different directions, we can assume that they are independent light. The reflected light corresponding to the recouplings of both type I and type II can be expressed as

$$R_{\text{I,II}} = 2T_L^{(j)}[1 - T_L^{(j)}]R_B^{(j)} \,. \qquad (4)$$

Hence, the maximum reflectivity is $R_{\text{I,II}} = R_B^{(j)}/2$, when $T_L^{(j)} = 1/2$.

Experimental investigations were carried out to verify the analysis presented above. The fibers used in our experiments were hydrogen-loaded commercial single-mode optical fiber (Corning SMF-28). The gratings were fabricated by irradiation of the fiber though a phase or amplitude mask with a scanning technique using a 248-nm KrF excimer laser. Their reflection and transmission spectra were measured by use of two optical spectrum analyzers (OSAs) simultaneously. The measured transmission spectrum of the FBG, with a period of 0.528 μm and a length of 2 cm, is shown in Fig. 2 (the OSA resolution was set to 0.02 nm for spectrum clarity), in which the loss spikes correspond to the contradirectional couplings to the backward guided and cladding modes. We also fabricated a weak LPG with a period of 450 μm and a length of 1.8 cm in the same fiber to form the concatenated grating structure. We applied a postexposure technique (i.e., with the LPG amplitude mask removed) to adjust the loss spikes in the transmission spectrum[7] and activate the recoupling behavior. The transmission spectra of the weak LPG before and after postexposure are shown in Fig. 3 (the OSA resolution was set to 2 nm for increased scanning speed for real-time monitoring). The FBG stopband appears weak because of the low-resolution setting of the OSA. To obtain maximum reflectivity $R_{\text{I,II}}$ we adjusted the loss at wavelength $\lambda_{\text{I,II}}$ to ~ -3 dB, as predicted by Eq. (3). It should be pointed out that a LPG written in a hydrogen-loaded optical fiber is not stable, and a small change of index modulation has significant

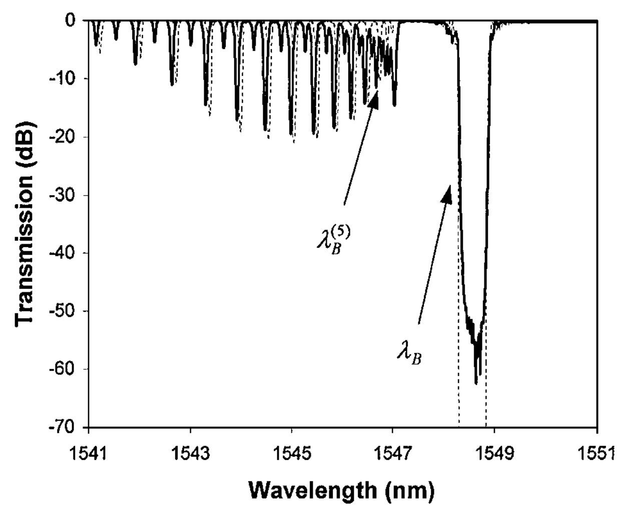

Fig. 2. Measured (solid curve) transmission spectrum of a strong FBG before the formation of the LPG. The resonant wavelength $\lambda_B^{(5)}$ is determined by comparison with the calculated result (dashed curve).

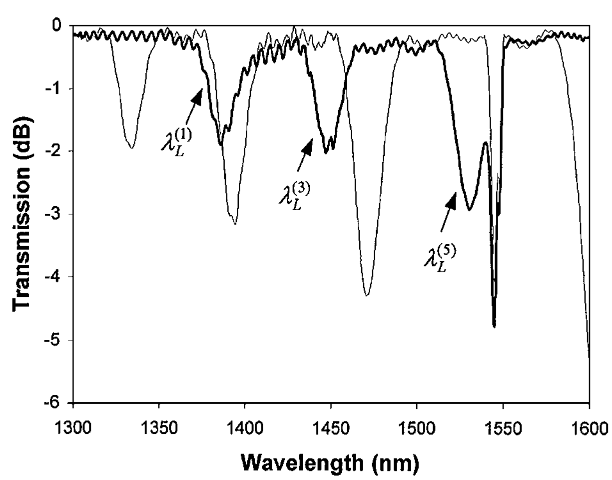

Fig. 3. Measured transmission spectra of the FBG and weak LPG before (light curve) and after (dark curve) postexposure.

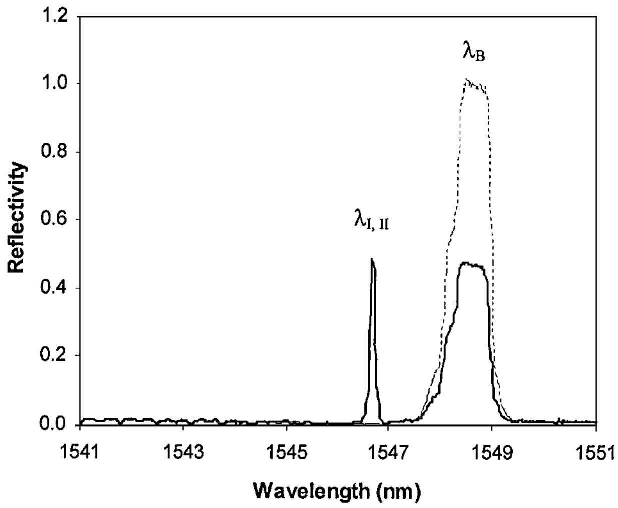

Fig. 4. Reflection spectra of the concatenated LPG and FBG (solid curve) and the original FBG (dashed curve).

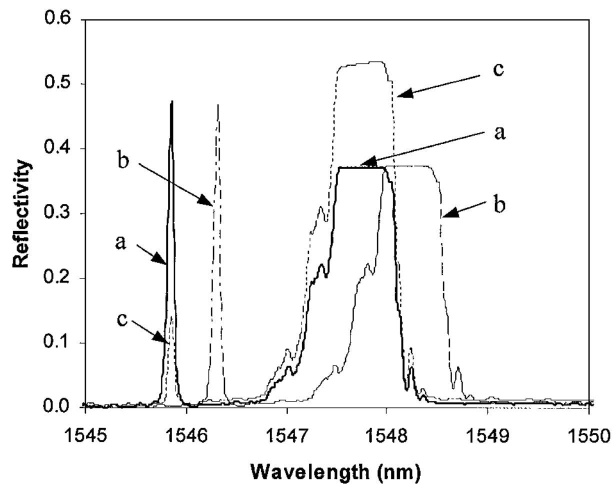

Fig. 5. Reflection spectra of the concatenated LPG and the FBG. a, free gratings; b, gratings under tension; c, gratings under bending.

effects on the transmission spectrum of the LPG as described by Eq. (1b). Hence, characterization of the corresponding effects induced by annealing processes is required for customizing the transmission spectrum of the LPG and for fabrication of such a special grating structure.

Figure 4 shows the measured reflection spectra of the concatenated grating structure and the original FBG. The Bragg wavelength, λ_B, of the FBG is located at 1548.6 nm, and the bandwidth is 0.73 nm. A reflectivity of ~100% was obtained, as shown in the corresponding stopband. With the introduction of the LPG, the reflectivity of FBG is decreased because of the loss of the LPG, whereas another peak appears because of the occurrence of recoupling mechanisms. The order of the cladding mode involved in the recouplings can be determined by the corresponding transmission spectra. As shown in Fig. 3, the loss spike corresponding to the $j = 5$ cladding mode was adjusted to be close to the Bragg wavelength of the FBG after the postexposure process. Hence, the observed reflection peak at 1546.7 nm results from the $j = 5$ cladding-mode-assisted recoupling in the concatenated grating structure, the resonant wavelength of which coincides well with $\lambda_B^{(5)}$, as denoted in Fig. 2. The reflectivities, $\tilde{R}_B$ and $R_{\mathrm{I,II}}$, of the presented grating structure are 47–48%. Since the light at wavelength λ_B is reflected completely to the backward guided mode, and more than 90% of light at wavelength $\lambda_{\mathrm{I,II}}$ is reflected to the backward $j = 5$ cladding mode, as shown in Fig. 2, the transmission $T_L^{(5)}$ of the LPG at the corresponding wavelengths λ_B and $\lambda_{\mathrm{I,II}}$ predicted by Eqs. (3) and (4) should be -1.61 and -2.29 dB, respectively. These predicted results agreed well with the measured results shown in Fig. 3.

The reflection spectra of another concatenated grating structure under tension and bending deformation are presented in Fig. 5, which demonstrates that both the resonant wavelength and the reflectivity can be tuned. When the grating structure is under tension, the spectral profile shifts to the longer-wavelength region. It can be seen from Eqs. (1) and (2) that the shift of resonant wavelength results from the induced change in the grating period and the effective indices of modes. Tuning of reflectivity by bending of the grating structure results from the bending loss and spectrum shift of the LPG, which can be explained by Eqs. (3) and (4).

In conclusion, we have presented an analysis of novel mode recouplings in a concatenated grating structure formed by a weak LPG and a strong FBG, and the recoupling mechanisms have been demonstrated experimentally. The guided mode coupled out to the cladding by the LPG is recoupled to the backward guided mode by the FBG, whereas the guide mode coupled to the backward cladding mode by the FBG can also be recoupled to the backward guided mode by the LPG. The unique reflection spectrum of such a structure, which has two reflection peaks resulting from different coupling behaviors, is a potential spectrum-tunable fiber-optic device and may also satisfy some multiparameter sensing applications.

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