Mode recoupling in a novel Bragg grating pair

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A new type of mode recoupling in a Bragg grating pair, in which one of the gratings is written in the fiber cladding, is proposed to overcome limitations of concatenated long-period and fiber Bragg gratings reported earlier [Opt. Lett. **27,** 1214 (2002)]. Its reflection spectrum is similar to that of the previously reported concatenated grating structure; however, the reflectivity can be much larger than the previous limitation of 50%. Furthermore, avoidance of the loss induced by a long-period grating makes such a Bragg grating pair more attractive for practical applications.

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Optical fiber gratings have become common light-wave components following the rapid development of grating writing techniques.[1] With increasing interest in fiber Bragg gratings (FBGs) and long-period gratings (LPGs), fiber grating structures have attracted much attention because of their special coupling behavior.[2,3] In a recent Letter the present authors and others reported a concatenated grating structure that comprises a weak LPG and another strong FBG, in which cladding-mode-assisted recouplings occur.[4] Such a structure can be used as a spectrum-tunable fiber-optic device and a novel multiparameter sensing element. The attraction of such a grating structure is its special reflection spectrum, which has two narrowband reflection peaks that result from different types of mode coupling. Despite its many advantages, such a concatenated grating structure has some inherent limitations. The first is that the reflectivity of such mode recoupling is limited to less than 50%. The second is the broadband loss induced by the LPG, which makes it less attractive in wavelength-division multiplexed systems. In this Letter we propose another grating structure, as shown in Fig. 1, whose reflectivity can be greatly increased to ~100%, that overcomes these limitations. In addition, the elimination of LPG makes it more attractive in practical sensing applications. The major difference between such a Bragg grating pair and conventional grating pairs is that one of the FBGs, labeled FBG-A, is written in the fiber cladding. Obviously the fabrication of such a grating needs a novel grating writing scheme with a special photosensitive fiber, such as fiber codoping[5] and postfabrication techniques. Here we demonstrate theoretically the special spectra of such a Bragg grating pair based on some measurable results and numerical simulation.

We consider mainly two types of mode coupling in such a Bragg grating pair. The first type is the conventional Bragg reflection of FBG-B, which is due to coupling from the forward guided mode to the backward guided mode. The second type is cladding-mode-assisted recoupling by the grating pair. The light coupled to the backward cladding mode by FBG-B will be reflected back by FBG-A and then coupled back to the guided mode by FBG-B. The merit of such a specially designed FBG-A is that it not only activates mode recoupling but also has little effect on the conventional Bragg reflection of FBG-B. The light should propagate in the direction from FBG-A to FBG-B for recoupling to occur.

Similarly to the discussion in Ref. 4, we consider gratings written in a single-mode fiber with a step-index profile, whose mode distributions are well known and described as guided and cladding modes.[6] Figure 2 shows the transmission spectrum of a strong FBG written in hydrogen-loaded Corning SMF-28 fiber. The period and the length of the grating are 0.5283 μm and 2 cm, respectively. The grating's depth of index modulation is 1.36×10^{-3}, which we determined by comparing the calculated results with the measured spectrum. These results show that a strong FBG not only reflects light to the backward guided mode but also reflects most of light to the backward cladding modes at the respective resonant wavelengths. Factually, the resonant wavelengths that correspond to various loss spikes in the

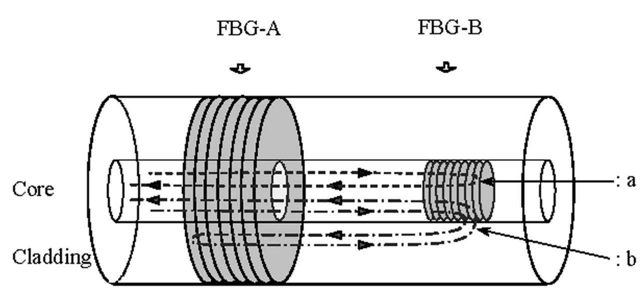

Fig. 1. Mode coupling in the novel Bragg grating pair: a, conventional Bragg reflection; b, cladding-mode-assisted recoupling.

transmission spectrum of FBG-B can be determined by the phase-matching condition as

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

where the superscripts $j = 0$ and $j = 1, 2, 3, \ldots$ denote the guided mode and different orders of cladding modes, $\lambda_B{}^{(0-j)}$ is the resonant wavelength for coupling between the guided mode and jth-order cladding modes, $n_{\mathrm{eff}}{}^{(j)}$ is the effective index of the jth-order guided and cladding mode, and Λ_B is the period of FBG-B. If the difference in effective indices in FBG-A and FBG-B is ignored, the grating period of FBG-A for activating the jth-order cladding-mode-assisted recoupling can be deduced from Eq. (1) and is expressed as

$$\Lambda_A = \Lambda_B \frac{\lambda_B{}^{(0-j)}}{2\lambda_B{}^{(0-j)} - \lambda_B}\,, \tag{2}$$

where Λ_A is the period of grating FBG-A and λ_B is the resonant wavelength $\lambda_B{}^{(0-0)}$ of conventional Bragg reflection. For convenience of comparison with the previously reported results,[4] the period of FBG-A is chosen to be 0.5293 μm to activate coupling with the fifth-order cladding mode ($j = 5$). As shown in the insets of Fig. 2, the mode distribution of such a cladding mode extends from the core to the cladding, whereas that of the guided mode is almost entirely confined in the fiber core. This is the basis for the design of the special FBG-A and the reason for using such a grating to interact with cladding modes.

The magnitude of reflectivity of a FBG is known to increase with the coupling coefficient, which is determined by both index modulation and mode distribution. Considering the coupling between the jth- and kth-order modes, we can write these relationships as

$$R^{(j-k)} \propto \kappa_{jk}\,, \tag{3a}$$

$$\kappa_{jk} = \frac{\omega}{4} \iint_A \mathbf{e}_j{}^*(x,y)\Delta\epsilon\,\mathbf{e}_k(x,y)\mathrm{d}x\mathrm{d}y\,, \tag{3b}$$

where $R^{(j-k)}$ is the reflectivity, κ_{jk} is the coupling coefficient, $\mathbf{e}_j$ is the normalized jth-order electric mode, and $\Delta\epsilon$ is the permittivity perturbation, which is proportional to the index modulation as $\Delta\epsilon = 2n\Delta n\epsilon_0$. The overlap integration in Eq. (3b) shows that the reflectivity of a Bragg grating is determined by both the magnitude of index modulation and the modulation area. To evaluate the effects of index modulation in the cladding on the grating's reflection capability, we show in Fig. 3 the simulated growth of reflectivity $R_A{}^{(5-5)}$ and $R_A{}^{(0-0)}$ of FBG-A with increasing index modulation, where the index modulation has been assumed to be uniform in the fiber cladding. It is clear from the figure that such a grating could reflect the cladding mode better than the guided mode if the position of the index modulation were altered.

When the light coupled by the FBG-B and the FBG-A is combined, the light reflected to the backward guided mode by the mode recoupling can be expressed as

$$R_r = R_B{}^{(0-j)}R_A{}^{(j-j)}R_B{}^{(j-0)} \qquad (j \neq 0)\,, \tag{4}$$

where $R_B{}^{(j-0)}$ is equal to $R_B{}^{(0-j)}$ owing to the reciprocal characteristic of a fiber grating. The hasty loss property of cladding modes make it difficult to measure the reflectivity $R_B{}^{(0-j)}$ for $j \neq 0$, which can be deduced only from the corresponding transmission spectrum. Figure 4 shows the calculated reflection $R_B{}^{(0-j)}$ of FBG-B for the coupling with cladding mode $j = 1, 3, 5$, etc., where for clarity the reflectivity is shown in linear coordinates. The reflections, $R_A{}^{(5-5)}$ and $R_A{}^{(3-3)}$, of FBG-A for the depth of index modulation that we used, 1.5×10^{-4}, are also given. The reflection peaks of $R_A{}^{(5-5)}$ and $R_B{}^{(0-5)}$ overlap well, thus resulting in the occurrence of mode recoupling. However, the reflection peak of $R_A{}^{(3-3)}$ does not overlap that of $R_B{}^{(0-3)}$, and therefore no mode recoupling occurs for cladding mode $j = 3$. Factually, the relationship between these reflection peaks is given by Eqs. (1) and (2) as

$$\frac{\Delta\hat{\lambda}_A}{\Delta\tilde{\lambda}_B} = \frac{2\lambda_B{}^{(0-j)}}{2\lambda_B{}^{(0-j)} - \lambda_B} \cong 2\,, \tag{5}$$

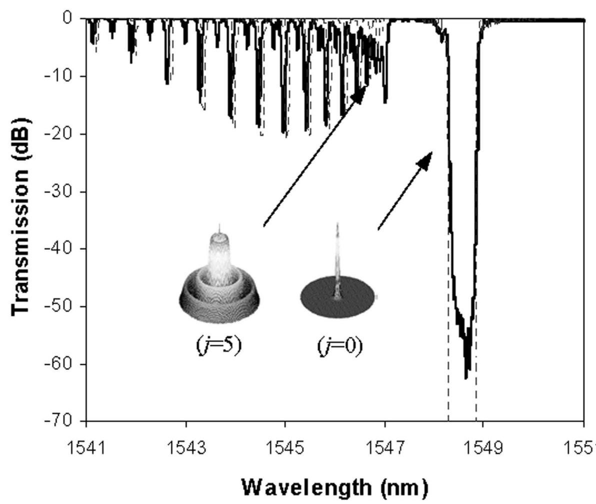

Fig. 2. Measured (solid curve) and calculated (dashed curve) transmission spectra of a strong fiber Bragg grating. Insets, electric mode distributions of cladding mode $j = 5$ and guided mode $j = 0$.

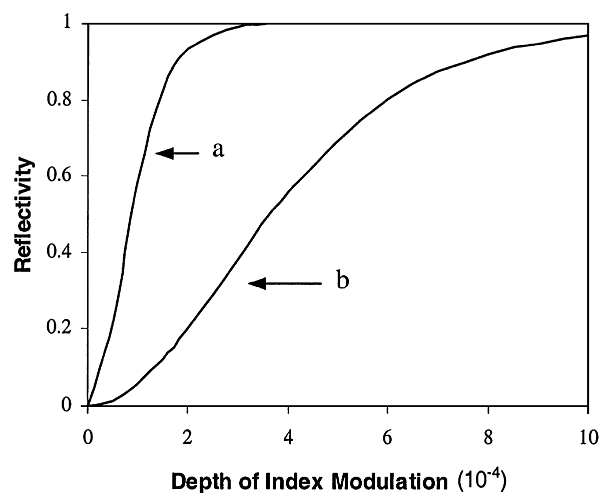

Fig. 3. Calculated growth of reflectivity with increasing index modulation: a, reflectivity $R_A{}^{(5-5)}$ at wavelength 1546.7 nm; b, reflectivity R_A at wavelength 1550.4 nm.

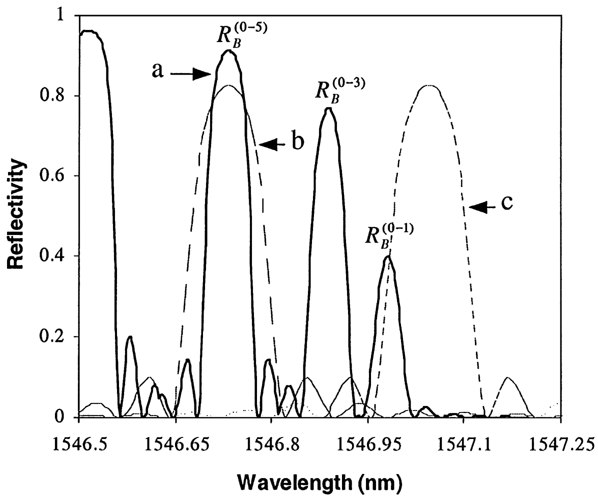

Fig. 4. Calculated reflection spectra of FBG-A and FBG-B: a, reflection spectrum $R_B{}^{(0-j)}$ of FBG-B with $j = 1, 3, 5$; b, reflection spectrum $R_A{}^{(5-5)}$ of FBG-A; c, reflection spectrum $R_A{}^{(3-3)}$ of FBG-A.

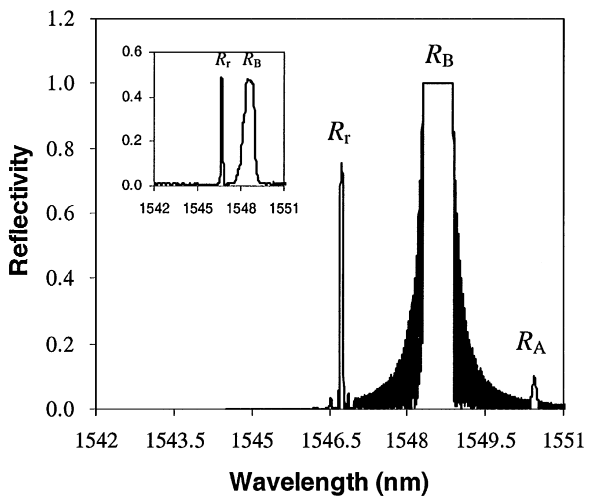

Fig. 5. Simulated reflection spectrum of the novel Bragg grating pair. The measured reflection spectrum of concatenated long-period and fiber Bragg gratings is shown in the inset for comparison.

where the peak distances are defined as $\Delta\hat{\lambda}_A = \lambda_A{}^{(j-j)} - \lambda_A{}^{(k-k)}$ and $\Delta\tilde{\lambda}_B = \lambda_B{}^{(0-j)} - \lambda_B{}^{(0-k)}$ for $k \neq j$. It guarantees that the FBG-A will activate only one mode recoupling.

Figure 5 shows the simulated reflection spectrum of such a Bragg grating pair. The reflection peak, R_r, results from mode recoupling, whereas the other two peaks, R_B and R_A, result from conventional Bragg reflection of FBG-B and FBG-A. If we compare the reflection spectra of the concatenated long-period and fiber Bragg gratings,[4] as shown in the inset of Fig. 5, we see that reflectivities R_r and R_B have increased from ~48 and 47% to ~75.2% and ~100%, respectively, at the same resonant wavelengths. The reflectivity of new reflection peak, R_A, is ~8.8%, with bandwidth ~0.07 nm, which we may further increase or suppress by changing the index modulation for a particular application. Some small peaks about these reflection peaks are induced by the sidelobes of FBG-A and FBG-B and can be eliminated by apodization. Because the narrowband light reflected by mode recoupling R_r passes through the fiber cladding, it provides a good sensing signal for an interrogation system based on a tunable optical filter to monitor or measure bending, vibration, and various environmental parameters.

In conclusion, we have proposed a novel Bragg grating pair, one grating of which is written in the fiber cladding, to overcome the limitations of concatenated long-period and fiber Bragg gratings reported earlier. The reflectivity of light by mode recoupling is no longer limited to ~50%. In particular, the avoidance of the loss induced by the LPG makes such a Bragg grating pair more attractive than the previously reported grating structure, which involves a LPG, in practical sensor applications. We thus expect that, because of its compelling advantages, the proposed novel grating structure will be extensively investigated and developed for a number of applications.

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