Ultrasensitive long-period fiber gratings for broadband modulators and sensors

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We demonstrate long-period fiber gratings whose attenuation can be changed by 25 dB over a 48-nm spectral band, with ambient-index changes of only 2.7×10^{-4}. To achieve this, the fiber waveguide is engineered to induce coupling between the core and a highly ambient-sensitive cladding mode with identical group velocities. The device schematic allows arbitrarily high index sensitivities to be achieved, which makes it an attractive platform for realizing sensors and modulators that respond to small index changes.

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Long-period fiber gratings (LPGs) couple light between copropagating modes of an optical fiber and have been used as spectral shapers,[1,2] mode converters,[3] and ambient-index sensors.[4,5] Ambient-index sensing with LPGs has attracted much attention, since the LPG is a resonant device that couples between the fundamental and cladding-guided modes of a fiber, with the cladding mode's propagation constant modulated by the ambient conditions.

Hence several studies have concentrated on improving the ambient-index sensitivity of LPGs. In this Letter the sensitivity is defined as the index change required for a 20-dB or larger change in transmitted intensity in the spectral range of interest. Patrick *et al.*[4] showed that the sensitivity monotonically increases as the ambient-index value approaches that of the glass cladding. Yin *et al.*[6] demonstrated that index sensitivities of 0.001 are achievable in fibers with a cladding etched down to 30 μm in outer diameter. Shu *et al.*[5] studied the sensitivity of LPGs for a variety of cladding modes and identified specific cladding modes that have index sensitivities of 0.01. A major drawback of using narrowband LPGs as index sensors is that the modulation of the resonant condition causes a spectral shift in a resonance. Such devices have inherent bandwidth-versus-extinction-ratio trade-offs. In addition, modulation of the intensity at one wavelength automatically leads to distortions at another wavelength, which may severely limit the application of LPGs as fast data modulators due to the addition of unwanted chirp in the signal. Ideally, a modulator would offer wavelength-insensitive, true-amplitude modulation.

It is possible to construct LPGs for which a shift in the resonant condition leads to true-amplitude modulation. Poole *et al.*[7] demonstrated that a few-mode fiber can be designed to have two modes with identical group velocities and that LPG coupling in that condition leads to broadband mode conversion. In this condition, called the turn-around-point (TAP) condition, LPG coupling occurs between the fundamental mode and a specific higher-order cladding mode.[5,8] Shu *et al.*[5] demonstrated true-amplitude modulation with index sensitivities of 0.01 by inducing coupling at the TAP. The unique spectral characteristics of TAP gratings are a strong function of the dispersive conditions for the two modes that are being coupled, and recently we demonstrated that the bandwidth, sensitivity, and spectral shape of such a resonance can be accurately tailored by dispersion engineering two core-guided modes with standard fiber design and manufacturing tools. Cladding modes are primarily guided by the glass cladding of a fiber, and such precise dispersion tailoring of these modes is obviously harder than in the case of core-guided modes. Likewise, sensitive TAP resonances demonstrated to date have been of significantly less-susceptible waveguide design and engineering—they occur at predetermined wavelengths, and the mode order defines the achievable sensitivity. The possibility of dispersion engineering in the cladding was recently theoretically postulated by Jeong and Oh[9] and may allow complex dispersion engineering to be used to tailor the bandwidth and coupling wavelengths of TAP resonances.

In this Letter we report the first demonstration, to our knowledge, of dispersion engineering in cladding modes to obtain TAP gratings with arbitrary bandwidth and ambient-index sensitivity, which can be induced in any desired spectral range. We demonstrate that this dispersive condition can be engineered in single-mode fibers (SMFs) coupling the fundamental mode to a cladding mode, regardless of the ambient condition of the LPG. This is used to demonstrate a LPG that exhibits 25-dB attenuation changes in response to an ambient-index change of only 2.7×10^{-4}. This novel LPG device overcomes the weakness of conventional LPGs—the ambient-index change results in modulation of the amplitude of the grating rather than a shift in its resonant wavelength, thus affording

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true-amplitude modulation. At the same time it offers an extinction ratio of more than 25 dB over a 48-nm spectral band, which can cover the entire C or L band. These two distinct properties, made possible by dispersion engineering of cladding modes, allow a LPG device to be constructed for which the amplitude can be changed by large amounts for arbitrarily small ambient-index changes. The fiber used for this device is similar to standard SMF, and hence it maintains its compatibility with fiber-optic transmission lines. Since the required index change is small enough to be similar to those afforded by electro-optic materials, this device schematic allows in-fiber data modulation.

The resonant condition for LPG coupling is given by[1]

$$\delta = \frac{1}{2}\left(\beta_{01} - \beta_{0m} - \frac{2\pi}{\Lambda}\right), \qquad (1)$$

where δ is the detuning parameter, Λ is the grating period, and β_{01} and β_{0m} are the propagation constants of the fundamental mode and the mth-order cladding mode, respectively. The condition $\delta = 0$ is called the phase-matching condition, and it represents the wavelength at which strong resonant coupling results. This condition may be plotted as a function of wavelength to yield a phase-matching curve (PMC). Although strong coupling occurs at resonance (when $\delta = 0$), the coupling magnitude decreases monotonically as δ departs from zero.

The PMC for the fiber used in our device is shown in Fig. 1(a). A unique feature is the existence of a TAP. A grating with a period that induces coupling at the TAP yields broadband spectra,[3,5] as shown in Fig. 1(b). Also shown in Fig. 1 are the PMCs and grating spectra for the same fiber with different ambient indices. A change in ambient index shifts the PMC such that the dashed horizontal line representing the grating period does not intersect the curve at any wavelength. The grating strength or amplitude decreases in proportion to the separation between the dashed line and the PMC, since the detuning δ becomes progressively larger. Ultimately, the PMC shifts far enough so that no resonance occurs. This yields an ambient-index sensor whose strength rather than resonant wavelength changes over a broad bandwidth.

Since the core mode is highly isolated from the ambient by the glass cladding of the fiber, β_{01} is insensitive to the surrounding material's index and slight changes of the cladding radius, whereas β_{0m} (of the cladding mode) is sensitive to small fluctuations in either parameter.

The sensitivity can be further increased if the fiber waveguide is engineered to have a TAP feature for any ambient-index value. To achieve this, the outer glass is etched slightly to engineer a waveguide with a cladding mode that always has a group velocity similar to that of the core mode. The relationship of the sensitivity of the LPG to changes in the ambient index can be analyzed with waveguide theory. The sensitivity of the propagation constant β_{0m} to n_{sur} can be calculated from the asymptotic expression[10]

$$\frac{\mathrm{d}\beta_{0m}}{\mathrm{d}n_{\mathrm{sur}}} = \frac{u_m^2 \lambda_{\mathrm{res}}^2}{n_{\mathrm{cl}} 4\pi^2 r_{\mathrm{cl}}^3} \frac{n_{\mathrm{sur}}}{(n_{\mathrm{cl}}^2 - n_{\mathrm{sur}}^2)^{3/2}}, \qquad (2)$$

where λ_{res} is the resonant wavelength, u_m is the mth root of the Bessel function of the first kind J_0 (m is the mode order), r_{cl} is the cladding radius, and n_{cl} and n_{sur} are the refractive indices of the cladding and ambient, respectively. Equation (2) indicates that the index change required for modulation of TAP LPGs decreases monotonically with increasing ambient index n_{sur}.

The fiber used for our experimental investigations is TrueWave RS, which is a SMF with $r_{\mathrm{cl}} = 62.5\ \mu\mathrm{m}$ and $n_{\mathrm{cl}} = 1.4573$. To fabricate the TAP LPG, the fiber was exposed to 248-nm UV radiation from an excimer laser through a chrome-plated amplitude mask. The TAP LPG is 5 cm long with a period Λ of 114 μm and a resonant wavelength λ_{res} of 1350 nm. Coupling is induced between the core mode and the $\mathrm{LP}_{0,14}$ cladding mode.

The TAP LPG is immersed in oils with different indices to study its response to various ambient-index conditions. As mentioned earlier, index changes serve to change the strength of the LPG. The index difference that changes the LPG strength from 0 to 25 dB is recorded for a variety of base index values of the oils. From Eq. (2) we note that the index sensitivity increases as the base index value approaches that of silica. Slightly etching the fiber ensures that the TAP feature of the PMC is maintained for a variety of ambient indices. We etched the fiber from 62.5 to 60 μm to maintain the TAP feature for oils ranging in ambient-index values between 1.42 and 1.45. Figure 2 shows the spectra for three fibers that were etched to yield TAP LPGs at the corresponding ambient-index values. An index change of $\sim 5 \times 10^{-3}$ is required (for 25-dB modulation) when the ambient

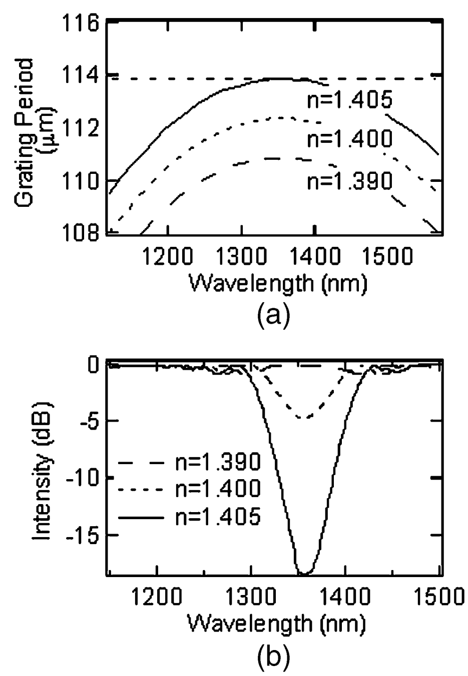

Fig. 1. (a) Phase-matching curve at different ambient indices. TAP yields a broadband spectrum. (b) Strength change instead of spectral shift with changing ambient index.

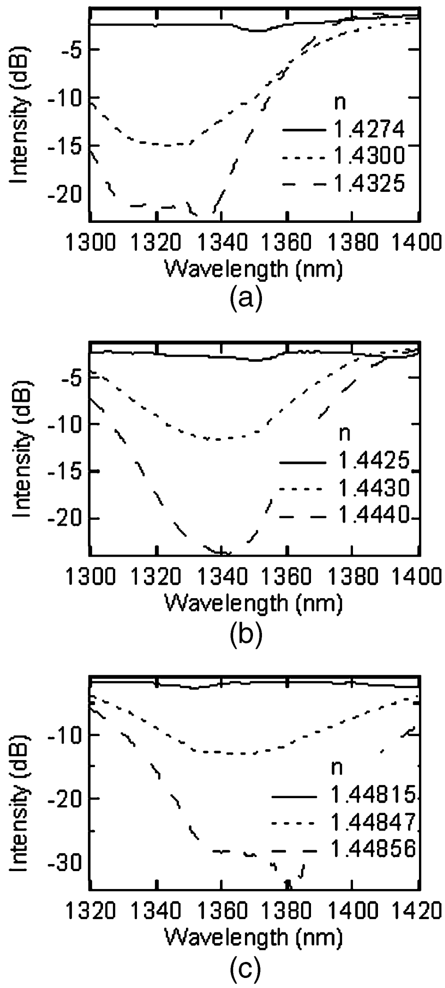

Fig. 2. Spectra of TAP LPG with different ambient indices. (a) Ambient index of 1.4325 yields a sensitivity of ~0.0050. (b) Ambient index of 1.4440 yields a sensitivity of ~0.0015. (c) Ambient index of 1.4486 yields a sensitivity of ~0.0004. Sensitivity increases as the ambient index approaches the silica index.

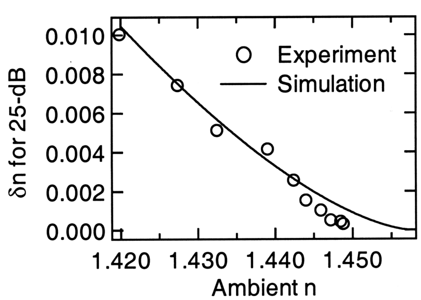

Fig. 3. Index sensitivity versus ambient index decreases monotonically. A record sensitivity of $\sim 2.7 \times 10^{-4}$ is observed. Theory matches well with experiment.

index is ~1.4325, but an index change of only 4×10^{-4} is required when the ambient index is 1.4486.

Figure 3 shows both the theoretical simulation based on Eq. (2) and the experimental results of index sensitivities for 25-dB modulation at various ambient-index values. The experimental results agree well with the theoretical simulation. The main reason for the error between them is the temperature-sensitive nature of the oil index. In experiments the highest sensitivity measured was 2.7×10^{-4} for 25-dB modulation over a 48-nm spectral band, which was obtained with an ambient index of 1.449. Note that further engineering of the cladding would have resulted in even higher index sensitivities, as is apparent from the theoretical curve.

In summary, we demonstrated an engineered cladding structure that yields LPGs that act as broadband, true-amplitude modulators with high sensitivity to the ambient index. To achieve this, we increased the surrounding material's index while maintaining the distinct TAP feature that yields the sensitive broadband attenuation. To the best of our knowledge, this is the highest sensitivity reported to date, and this was achieved in fibers with dimensions similar to standard fibers. This allows, for the first time, ultrasensitive sensors, as well as the prospect of weak electro-optic modulation with in-fiber TAP LPG devices.

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