Postfabrication resonance peak positioning of long-period cladding-mode-coupled gratings

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A simple, flexible method of postfabrication positioning of resonance wavelengths of long-period cladding-mode-coupled gratings is proposed. This method is based on changing the outer fiber diameter. Reducing the diameter by etching the fiber in HF acid shifts the loss peaks to higher wavelengths. A shift as large as 130 nm after 5 min of HF etching was observed for our strongest grating peak, corresponding to the cladding mode HE_{19}. The experimental results are in excellent agreement with model calculations. © 1996 Optical Society of America

Photoinduced long-period cladding-mode-coupled gratings[1] can successfully be used in optical fiber communications systems, for example, for gain spectrum flattening of Er-doped fiber amplifiers[2] and for removing undesirable Stokes orders in cascaded Raman amplifiers. The grating resonance wavelengths, the intensities of resonance peaks, and the bandwidth can be chosen in accordance with the application requirements. These parameters are related to one another, and we define them simultaneously by selecting the following parameters: amplitude of the grating-induced refractive index, length, and period. In practice, the grating writing procedure is limited by the discrete set of available amplitude masks. Moreover, during the long-period grating fabrication there is a strong displacement of resonance peaks owing to the increase of the mean refractive index of the fiber core.[3] For standard writing techniques the accuracy in positioning the peak for a desired peak intensity is limited to a few nanometers. In this situation it is very important to have a procedure to decorrelate peak position and intensity after the grating preparation.

In this Letter we present a simple technique to tune precisely and continuously the resonance wavelengths of long-period cladding-mode-coupled gratings without strongly affecting the coupling strength. The main principle of this method is based on the strong dependence of the propagation constants and hence the peak positions of the cladding modes on the cladding diameter. Therefore one can shift the grating resonance wavelength by changing the cladding dimension. We have achieved this by etching the fiber in a HF acid solution.

Long-period gratings were written in a single-mode germanosilicate fiber with a cutoff wavelength of 0.92 μm. The fiber has a step-index profile with 12 mol. % GeO_2 in the core and a cladding diameter of 125 μm. The fiber was irradiated by a KrF excimer laser ($\lambda = 248$ nm) through an amplitude mask with a period of $\Lambda = 200$ μm. An energy density of 85 mJ/cm^2/pulse, a pulse repetition rate of 50 Hz, and an irradiation time of 1 h were typically applied. A halogen lamp and a 1-m focal-length monochromator were used for characterizing the gratings. A typical resolution of our transmission measurements was 1 nm. We carried out computer modeling, taking into account real fiber parameters, assuming a step-index profile in the fiber core, and considering the rectangular distribution of the induced refractive-index change in the core along the fiber axis. Fundamental (β_{core}) and cladding-mode (β_{clad}) propagation constants were calculated as described in Ref. 4. The resonance wavelengths were obtained from the phase-matching conditions between the modes considered:

$$\beta_{\rm core} - \beta_{\rm clad} = \frac{2\pi}{\Lambda}\,. \qquad (1)$$

The coupling coefficient η was calculated in accordance with the following equation[5]:

$$\eta = \frac{\pi \Delta n^{\rm ind} I}{\lambda_r}\,\frac{4}{\pi}\,, \qquad (2)$$

where $\Delta n^{\rm ind}$ is the amplitude of UV-induced refractive-index modulation, I is the overlap integral between the core and the cladding modes in the core region, and λ_r is a resonance wavelength. The additional factor $4/\pi$ accounts for the rectangular shape of the induced index profile along the fiber core. The resonance peak intensity S in the case of two copropagating modes can be written as[5]

$$S = \sin^2(\eta L)\,, \qquad (3)$$

where L is the grating length.

Figure 1 shows the experimental (solid curve) and the theoretical (dashed curve) transmission spectra of a 17-mm-long grating. Eight resonance peaks showing the coupling between the fundamental (HE_{11}) and

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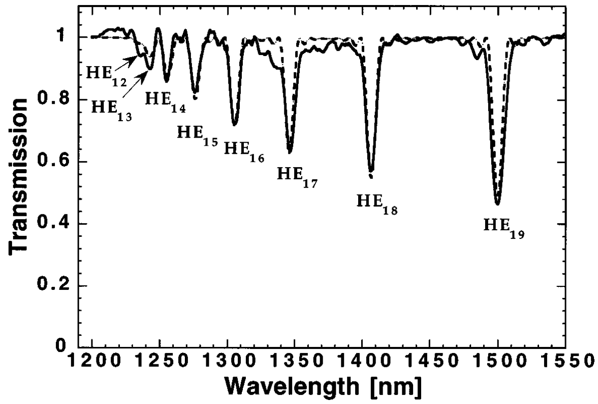

Fig. 1. Experimental (solid curve) and theoretical (dashed curve) transmission spectra of a long-period grating with 17-mm length ($\Lambda = 200\ \mu$m).

the radially symmetric (HE_{1m}, $m = 2, \ldots, 9$) modes were observed in the measured wavelength range. A very good agreement between the theoretical and the experimental spectra is obtained for $\Delta n^{\text{ind}} = 4.7 \times 10^{-4}$. Slight deviations in bandwidth might be the result of grating nonuniformity.

Figure 2 represents the change of the initial transmission spectrum after 5 min of etching. For silica etching we used a 40% solution of HF. We obtained a mean etching rate of $1.9 \pm 0.1\ \mu$m/min by measuring the fiber diameter with the aid of an optical microscope at regular time intervals. The grating peaks are shifted toward the long-wavelength part of the spectrum. The total shift depends strongly on the cladding-mode order. The displacement was ~130 nm for the highest cladding mode in our spectrum (HE_{19}). A small increase in peak intensity of the etched grating is observed. A slight broadening of the bandwidth, possibly owing to variations of the diameter induced by inhomogenous etching, is also observed.

The experimental and theoretical dependencies of the resonance wavelengths on the change of the cladding diameter are presented in Fig. 3. The experimental results are in excellent agreement with the theoretical predictions. The sensitivity of peak position to the diameter change increases with increasing radial mode order m. For the first cladding mode this sensitivity is almost constant, with a value of 0.05 nm/μm, and the highest observed cladding mode exhibits a value ranging from 10 to 25 nm/μm. The increase of sensitivity with increasing mode order is defined by the waveguiding properties of the fiber. The same behavior was observed for the dependence of the sensitivity of the peaks' positions on external influences, such as temperature, bending, and the refractive index of the surrounding medium.[6]

The normalized intensities of the resonance peaks of five cladding modes are plotted in Fig. 4 as a function of the cladding-diameter change. Qualitative agreement between experiment and theory is observed. The peaks' intensities increase slightly during the fiber etching. This phenomenon can be explained by the increase of the overlap integral between fundamental and cladding modes owing to compression of the cladding-mode field and should be taken into consideration in grating spectrum design.

In conclusion, we have shown that one can achieve postfabrication tuning of resonance wavelengths

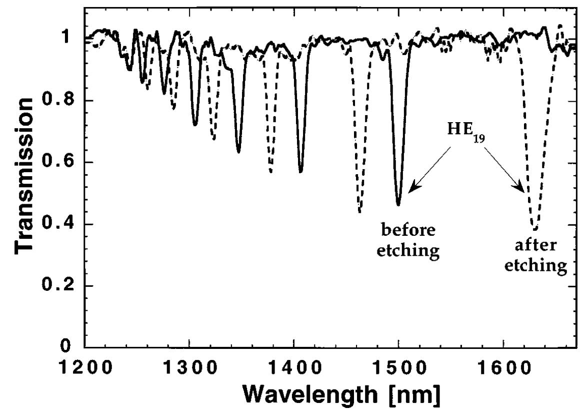

Fig. 2. Initial spectrum (solid curve) and the spectrum after 5 min of HF etching (dashed curve) for a long-period grating (see grating parameters in text).

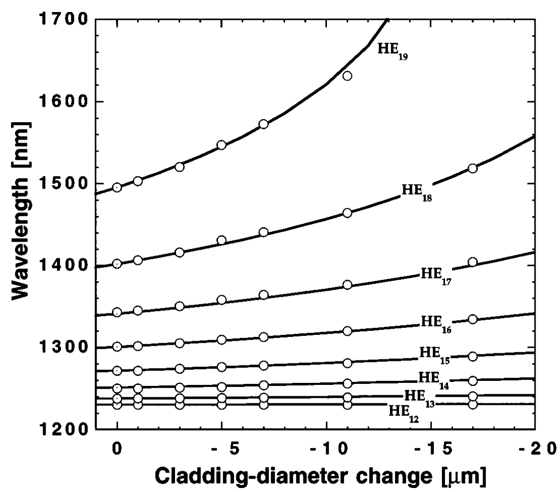

Fig. 3. Experimental (circles) and theoretical (curves) resonance wavelengths' positions as a function of cladding-diameter change.

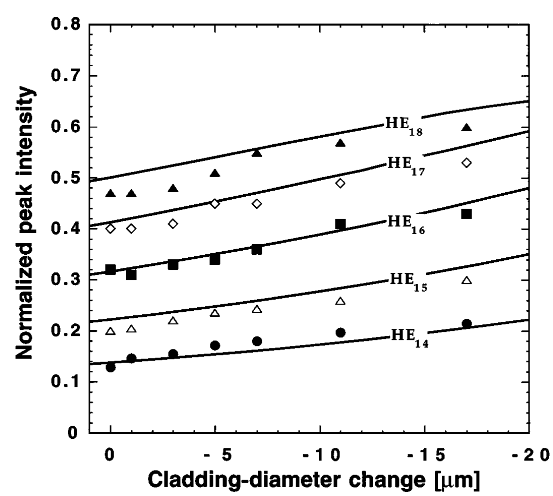

Fig. 4. Experimental (symbols) and theoretical (curves) normalized peaks' intensities as a function of cladding-diameter changes.

of long-period cladding-mode-coupled gratings by changing the cladding diameter, using HF acid. This method has the following advantages:

- Reasonable decorrelation of peak position and peak intensity.
- Permanence of induced spectral changes.
- Rapid peak displacement (up to 26 nm/etching minute in a 40% solution of HF acid).
- *In situ* peak adjustment during etching. In this case the high sensitivity of the peaks' positions to the index of the surrounding medium[1,6] should be taken into consideration.

In addition, the high sensitivity of peak position for higher-order cladding modes can be used for precise measurements of the silica etching rate and the acid concentration. The estimated accuracy of the fiber-diameter determination can be better than 50 nm when an accuracy of peak position measurement of 1 nm is assumed.

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