Displacements of the resonant peaks of a long-period fiber grating induced by a change of ambient refractive index

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We present a graphic method of analyzing the spectral displacements of a long-period fiber grating as a function of ambient index. Mode dependence of the maximum displacement, disappearance of a particular resonance peak, and spectral behavior when the ambient index is larger than that of the cladding material are investigated and compared with experimental results. © 1997 Optical Society of America

Long-period fiber gratings (LPG’s) have many applications as filters for fiber-optic telecommunications and as sensors for strain, temperature, and refractive-index measurements.1,2 The fundamental guided mode propagating along the core of a single-mode fiber is coupled to forward-propagating cladding modes through a grating photowritten along the core of the fiber.3 Because the cladding of a single-mode fiber supports many cladding modes, a LPG has many resonance peaks. It was recently reported that the spectral resonance peaks of a LPG are shifted by the refractive-index change of the ambient around the cladding.4,5 As the ambient index is increased, each resonance peak first shifts toward the shorter-wavelength direction and then disappears. When the ambient index is larger than that of the cladding, the resonance peaks reappear at slightly longer wavelengths than those measured in ambient air. However, the maximum possible spectral displacement of each resonance peak and the reason that the reappearing resonance peak has a longer wavelength have not been explained. Here we present a theoretical analysis of the spectral displacements of a LPG, using a graphic method, and compare it with our experimental results.

The phase-matching condition of a LPG2 is generally given as a function of mode indices of the core, n_{0c}, and the cladding, n_{0p}:

$$\lambda_p = (n_{0c} - n_{0p}) \Lambda,$$

where \( \Lambda \) is the period of the grating, \( p \) is the mode number, and \( \lambda_p \) is the wavelength of the \( p \)th-order resonance peak. The effective indices of the core and the cladding modes are given as functions of the propagating wavelength, the geometry of the fiber, and the refractive indices of the core and the cladding materials. For a weakly guiding step-index fiber, a geometric-optics approximation6 is generally used to yield the mode indices of the core and the cladding modes. Because a single-mode fiber can support only the LP_{01} mode, the mode equation for the core mode is

$$\left[ n_{core}^2 - (n_{0c})^2 \right]^{1/2} - \frac{\pi}{2} = 2 \cos^{-1} \left[ \frac{(n_{core})^2 - (n_{0c})^2}{(n_{core})^2 - (n_{clad})^2} \right]^{1/2},$$

where \( D_{core} \) is the diameter of the core. Equation (2) shows that the effective index of the core mode, \( n_{0c} \), is given simply as a continuous function of wavelength and some known physical parameters of the fiber. Plugging this calculated effective index of the core into Eq. (1), we get the expression for the effective index of the \( p \)th-order cladding mode as a function of wavelength.

The equation for the LP_{0p} cladding mode, when the diameter of the cladding is much larger than that of the core, is approximately given as

$$\left[ n_{clad}^2 - (n_{0p})^2 \right]^{1/2} - \left( p - \frac{3}{4} \right) 2 \pi = 2 \cos^{-1} \left[ \frac{(n_{clad})^2 - (n_{0p})^2}{(n_{clad})^2 - (n_{amb})^2} \right]^{1/2},$$

where \( D_{clad} \) is the diameter of the cladding and \( n_{amb} \) is the refractive index of the ambient around the cladding. When \( n_{amb} \) is larger than \( n_{0p} \), the right-hand side of Eq. (3) becomes a constant of \( \pi \). Plugging the effective indices calculated in Eqs. (2) and (1) into Eq. (3), we get the equation for the wavelength of the \( p \)th-order resonance peak as a function only of ambient index.

The left-hand side of Eq. (3) physically means the transverse component of the phase change, in modulus \( 2 \pi \), of a beam propagating across the cladding of the fiber. The right-hand side represents the phase shift that is due to the total internal reflection (TIR) at the interface between the cladding and the ambient. To show the overall behavior of the spectral displacements we plot both sides of Eq. (3) simultaneously as a function of wavelength, as depicted in Fig. 1. The dotted curves are plots of the left-hand side of Eq. (3)
modulus $2\pi$, and the solid curves are plots of the right-hand side at several ambient indices. The points of intersection of the two sets of curves are the wavelengths of the resonance peaks. From Eqs. (1) and (3), the solid curves hit the horizontal axis when

$$\lambda_c = (n_0/c_0 - n_{amb})/\Lambda. \quad (4)$$

This is the critical wavelength where the propagation angle becomes the critical angle for TIR. Above the critical wavelength the resonance wavelengths are determined by the points of intersection of the solid curves and a constant $\pi$ because the phase shift induced by the reflection above TIR becomes $\pi$.

As $n_{amb}$ increases, from Eq. (4) the critical wavelength decreases; therefore all the resonance wavelengths below the critical wavelength decrease. When the ambient is air, the phase shift that is due to TIR is calculated as depicted by curve a of Fig. 1. Curve b is the phase shift with an ambient index of 1.44. When the critical wavelength approaches the minimum wavelength of a certain mode, the resonance wavelength of that mode approaches the maximum displacement and then disappears owing to the poor reflection just above the TIR, which is depicted by curves c and d of Fig. 1. When the refractive index of the ambient is increased further, the lower-order modes also disappear one by one. For an example, with the condition of curve d the fourth-order mode disappears and only the three other lower modes are left. Near the refractive index of the cladding all modes disappear or weaken greatly. With an ambient index larger than the cladding index the resonance peaks reappear at wavelengths slightly longer than those measured in ambient air. The wavelength of the reappearing peak has no further dependence on the ambient index, but the depth of each peak increases with increasing ambient index because of the increasing reflectivity of the cladding–ambient interface.

The calculated wavelength of each resonance peak is depicted in Fig. 2 as a function of the ambient index. Near the refractive index of the cladding, 1.444, each mode has the maximum spectral displacement, which is finite and depends on the order of resonance. From Figs. 1 and 2 we can conclude that each mode has a finite amount of maximum displacement and that a higher mode has a longer displacement. With an ambient index higher than that of the cladding, each resonance peak reappears at a wavelength slightly longer than that measured in air.

A 25-mm-long LPG was made in a step-index single-mode fiber with an amplitude mask of a period of 400 $\mu$m. The fiber was loaded with hydrogen and exposed to a KrF laser of 200-mJ/pulse energy. The LPG was placed upon an anodized aluminum plate with no strain intentionally applied, and a series of refractive-index oils, and some mixture of them, was dropped upon the LPG. The transmission spectra of the LPG with several ambient indices were measured with an optical spectrum analyzer. The measured spectral displacements of the fourth-order resonance peak were plotted and fitted with the calculated curve in Fig. 3 as a function of the ambient index. The
Figure 4 is a set of transmission spectra taken at several ambient indices. Curve (a) of Fig. 4 is the spectrum taken when the ambient is air and has two resonance peaks of modes 3 and 4 within the given wavelength range. Near the cutoff wavelength of the fourth-order mode the spectral displacement of the fourth-order resonance peak was $-48$ nm, as depicted in curve (b). With a slight increase in the ambient index the fourth-order resonance peak almost completely disappeared, whereas the third-order resonance peak shifted further, as shown in curve (c); then both peaks disappeared, as shown by curve (d). Curves (c) and (d) were taken when the ambient indices were $1.456 - 1.46$, specified at a wavelength of $589.3$ nm. Above an ambient index of $1.46$, both peaks reappeared with positive spectral displacement; for example, for the fourth-order resonance peak the positive displacement was $+2$ nm. After that displacement, no further spectral displacement was measured up to an ambient index of $1.64$, but both resonance peaks got deeper. The spectrum with an ambient index of $1.64$ is depicted in curve (e) of Fig. 4.

In conclusion, the spectral displacement of a LPG induced by a change of ambient index has been explained by a phase shift at the interface between the cladding and the ambient. The overall spectral behavior can be visualized by a graphic method based on geometrical-optics. With increasing ambient index, the resonance peaks move toward the shorter-wavelength direction, disappear one by one from a higher- to a lower-order mode, and then reappear at slightly longer wavelengths than those measured in ambient air. After the reappearance there is no more spectral displacement, but the depth of each resonance peak that has reappeared increases. The maximum spectral displacement of a higher-order mode is wider than that of a lower-order mode.

References