Radiation-mode coupling loss in tilted fiber phase gratings

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We demonstrate that grating tilt is an important adjustable parameter that can be utilized in addition to the more familiar parameters of grating length and index change to tune the spectral shapes of fiber phase gratings designed to perform demanding filter applications through guided-mode to radiation-mode coupling loss. A comparison is made between calculated transmission spectra obtained from a coupled-mode-theory analysis and measured spectra obtained from strong gratings written by ultraviolet irradiation of deuterium-sensitized fiber with grating tilt angles ranging from 0° to 15°. We show that good agreement is obtained between the experimental measurements and the theoretical predictions. © 1995 Optical Society of America

The fiber phase grating written by UV light into the core of an optical fiber has found many useful applications as a wavelength-selective, guided-mode reflector. But such gratings also couple guided modes to radiation modes of the fiber. An analysis of radiation-mode coupling loss in fiber phase gratings was described in a recent paper by Mizrahi and Sipe. This loss can be problematic for devices designed to utilize strictly grating reflection. However, it can be used to advantage for numerous applications, such as gain-spectrum flattening, filtering of amplified spontaneous emission, and pump-light rejection in optically amplified optical communications systems, as well as spectral clean-up filtering in wavelength-division-multiplexed systems. Such applications demand filters with high spectral bandwidth (≤10 nm), low insertion loss (≤1 dB), low backreflection (≤-50 dB), and low cost, which results from mass producibility and packaging simplicity. While bulk filters offer suitable spectral performance, they frequently suffer from packaging complexity and difficulty in achieving low insertion loss. Fiber phase gratings can potentially meet the high demands listed above. Broadband, guided-mode reflection gratings utilizing strong chirp offer one possibility, but in many cases reflection is not desired, and an isolator must be present to limit backreflection problems. As a result, radiation-mode coupling loss appears to be the most feasible method for achieving broadband filtering with fiber gratings. We note that this coupling can be accomplished through both backscattering in short-period gratings and forward scattering in long-period gratings. For simplicity, we consider only the short-period grating case here.

Since the first reported discussions of radiation-mode coupling in fiber gratings, it has been recognized that this coupling can be enhanced and to some extent controlled, for example, directionally, by tilting the fringes of the phase grating. Variation of grating tilt affects the amount of coupling loss, the width of the loss spectrum, the separation of the wavelength region at which maximum loss that is due to radiation-mode coupling occurs from that at which Bragg reflection occurs, and the Bragg reflection spectrum. The last of these is important for filter applications that cannot tolerate any reflection, for which the ability of grating tilt to diminish Bragg reflection while simultaneously enhancing radiation-mode coupling is advantageous.

In this Letter we experimentally and theoretically characterize radiation-mode coupling loss in UV-induced tilted fiber phase gratings written in a standard, step-index optical fiber. The main emphasis here is on how the properties of the loss spectrum depend on the grating tilt angle. This dependence has not, to our knowledge, been described elsewhere and is vital to the design of devices that utilize radiation-mode coupling loss. Although a detailed understanding of the dependence of Bragg reflection properties on grating tilt angle is also practically important, we defer this analysis to another paper, in which we also describe in detail the theory used to generate the calculated results presented here. We show below that the measured grating loss spectra agree quite well with a coupled-mode-theory calculation.

To investigate the dependence of the radiation-mode coupling loss spectrum on tilt angle experimentally, we wrote a set of nominally identical gratings at various tilt angles. The grating periods are roughly 0.5 μm, so that for wavelengths in the vicinity of 1.5 μm coupling of a forward-going guided mode to backward-going radiation modes is observed. In principle, a similar characterization could be done for codirectional coupling with long-period gratings, but we concentrate exclusively on the contradirectional case.

Corning Flexcore fiber was chosen for these experiments because of its nearly step-index profile. The fiber had a core radius of a = 2.625 μm and Δ = 0.0055. It was loaded with approximately 3.8 mol.% of deuterium to enhance its photosensitivity. We wrote the gratings by interfering two beams from a 242-nm, excimer-laser-pumped, frequency-doubled dye laser producing 15-ns pulses at a 30-Hz repetition rate. Exposures were done with 20 mW of average power, with the nearly Gaussian beam focused to a spot size of approximately 5 mm × 50 μm on the fiber. Exposure times varied from 1 to 2 min; the transmission spec-
trum was monitored in real time to achieve roughly the same UV-induced index change for all gratings. The index change is approximately $\Delta n/n_{\text{eff}} = 1.0 \times 10^{-3}$, where $n_{\text{eff}}$ is the effective refractive index of the guided mode for which the grating is designed and $2\Delta n$ is the peak-to-peak induced index change assuming perfect fringe visibility. It is important to note that, because of variations in interferometer alignment and stability between the writing of successive gratings, there is a noticeable variation in both grating fringe visibility and UV-induced index change among the gratings.

The grating tilt was achieved by rotation of the fiber about the axis normal to the plane defined by the two intersecting UV beams (see Fig. 1). Using Snell’s law, we can write a grating with a design Bragg wavelength of $\lambda_0^\text{cl}$ and a grating tilt angle of $\theta$, using a UV beam intersection angle in air of $2\alpha_{\text{ext}}$ and an external tilt angle $\theta_{\text{ext}}$, given by

$$2\alpha_{\text{ext}} = \arcsin[n_{\text{cl}} \sin(\alpha + \theta)] + \arcsin[n_{\text{cl}} \sin(\alpha - \theta)],$$

$$\theta_{\text{ext}} = \frac{1}{2} \arcsin[n_{\text{cl}} \sin(\alpha + \theta)] - \frac{1}{2} \arcsin[n_{\text{cl}} \sin(\alpha - \theta)].$$  \hspace{1cm} (1)

Here $2\alpha$ is the beam intersection angle inside the fiber, approximately determined by the equation

$$\sin \alpha = (n_{\text{eff}}/n_{\text{cl}})(\lambda_{\text{UV}}/\lambda_0^\text{cl} \cos \theta),$$  \hspace{1cm} (2)

where $n_{\text{cl}}$ is the cladding refractive index. Figure 2(a) shows a plot of the experimentally measured transmission loss spectra for gratings with tilt angles as high as 15°. Here wavelength detuning is defined relative to the design Bragg wavelength. For these measurements the bare fiber was submerged in a suitable index-matching fluid to suppress effects associated with cladding-air interface reflections. In the absence of matching fluid, the otherwise smooth loss spectrum demonstrates Fabry-Perot oscillations; these can also be interpreted as discrete resonances associated with coupling between the guided mode and cladding modes of the fiber. Equivalently, the bare fiber can be recoated with a suitable polymer coating.

In order to understand more fully the measured spectra of Fig. 2(a), we used a coupled-mode-theory analysis to calculate the transmission loss spectra resulting from coupling of a forward-going LP_{01} guided mode to the continuum of backward-going LP_{0} radiation modes, where $q$ is the azimuthal mode number. The analysis is analogous to the development described in Ref. 2. As shown in that development, at wavelengths for which the only appreciable coupling occurs between the forward-going LP_{01} guided mode of amplitude $a^+ (z)$ and backward-going radiation modes, the amplitude $a^+ (z)$ evolves according to

$$\frac{da^+ (z)}{dz} = -\beta \alpha (z) a^+ (z),$$  \hspace{1cm} (3)

where

$$\alpha (z) = \kappa (z) \sum_q \frac{\beta}{\rho} |\nu_{aq,01}^{-+}|^2.$$  \hspace{1cm} (4)

These equations are identical to Eqs. (14)–(16) of Ref. 2, and the symbols are as defined in Ref. 2: $\kappa (z)$ is the slowly varying normalized amplitude of the periodic effective refractive-index perturbation that defines the grating, $\beta$ is a reference propagation constant, $\beta$ is the radiation-mode propagation constant (along $z$), and $\rho = (2\pi n_{cl}/\lambda)^2 \beta^2 \nu^{+2}$ labels the radiation mode of interest. The difference between the current analysis and that in Ref. 2 is that the coupling coefficients $\nu_{aq,a'q'}$ in Eq. (4) reflect the presence of grating tilt at an angle $\theta$ according to

$$\nu_{aq,a'q'} = \frac{\pi c v_0}{2} \frac{1}{P_{aq} P_{a'q'}} \int_{\text{core}} \tilde{E}_{aq}^*(x, y) \times \exp \left(-2i \frac{2\pi}{\Lambda} x \sin \theta \right) \tilde{E}_{a'q'}^+(x, y) dx dy.$$  \hspace{1cm} (5)

For an untitled grating ($\theta = 0$), Eq. (5) simplifies to Eq. (12) of Ref. 2. Here the $x$ and $y$ directions are parallel to the $p$ and $s$ directions, respectively, shown in Fig. 1, and the $z$ direction is parallel to the fiber axis. Also, $\Lambda$ is the grating period measured perpendicular to the grating lines, such that the design wavelength for LP_{01}–LP_{01} Bragg reflection is given by $\lambda_0^0 = 2n_{\text{eff}} \Lambda / \cos \theta$.

To simplify the calculations a number of approximations were made that should not significantly affect the results, including the customary coupled-mode-theory approximations (such as the assumption of a single-grating Fourier component and the use of the synchronous or rotating-wave approximation) and the exclusion of depolarized scattering (i.e., only $s$-polarized guided-mode to $s$-polarized radiation-mode coupling is considered, as defined in Fig. 1). Furthermore, only LP_{0} radiation modes with $0 \leq q \leq 5$ are included in the calculation. For wavelengths well below the design wavelength and for very large tilt angles, higher azimuthal-order radiation modes should be included; for the range of wavelengths and tilt angles considered here, the single LP_{0} radiation modes are sufficient to describe the transmission spectra.

![Fig. 1. Diagram of a step-index optical fiber showing a tilted fiber phase grating. Also shown are the rays representing two UV beams incident upon the fiber during grating writing and their associated angles inside and outside the fiber.](image)
In Fig. 2(b) the calculated transmission loss spectra corresponding to the measured spectra in Fig. 2(a) are plotted. There is reasonably good agreement between the measured and calculated spectra. As pointed out above, because of variation in the actual UV-induced index change and the fringe visibility among the gratings, the most accurate comparison of the spectra in Fig. 2(a) with each other and with the calculated spectra in Fig. 2(b) should be based on spectral shape, rather than on the actual value of transmission loss at any given wavelength. For example, Fig. 3 shows that there is good agreement of the measured wavelengths of maximum loss (circles) versus tilt angle with the calculated wavelengths (solid curve).

In conclusion, we have demonstrated the spectral characteristics of radiation-mode coupling loss in a tilted fiber phase grating for a large range of grating tilt angles, showing that grating tilt is a valuable adjustable parameter for achieving application-tailored filter shapes. The measured grating transmission spectra were found to agree well with calculated results from a coupled-mode-theory analysis. In general, as the grating tilt angle is increased from $0^\circ$, the maximum coupling loss first increases slightly and then decreases significantly, the spectral width over which significant loss occurs (relative to the maximum) increases, and the wavelength of maximum loss decreases.

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References