Formation of Bragg gratings in optical fibers by a transverse holographic method

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Bragg gratings have been produced in germanosilicate optical fibers by exposing the core, through the side of the cladding, to a coherent UV two-beam interference pattern with a wavelength selected to lie in the oxygen-vacancy defect band of germania, near 244 nm. Fractional index perturbations of approximately 3×10^{-5} have been written in a 4.4-mm length of the core with a 5-min exposure. The Bragg filters formed by this new technique had reflectivities of 50–55% and spectral widths, at half-maximum, of 42 GHz.

In 1978, Hill *et al.*[1,2] reported the formation of refractive-index gratings in germanosilicate fiber by sustained exposure of the core to the interference pattern of oppositely propagating modes of 488- or 514.5-nm argon-ion laser radiation. Subsequent investigations by Lam and Garside[3] showed that the grating strength increased as the square of the writing power, which suggested a two-photon process as the cause of the index changes. This Letter presents the first results to our knowledge that show that in-fiber Bragg gratings can also be formed by illuminating the core from the side of the fiber with coherent UV radiation that lies in the 244-nm germania oxygen-vacancy defect band.[4–6] This intense absorption band, which is ~35 nm wide, coincides with the second harmonic of both blue-green argon-ion laser lines used in previous research.

The index modulation, which can be selected to correspond to a desired Bragg wavelength, is written within the core by exposing it to a two-beam interference pattern. The grating period is determined by the incident wavelength and the included angle between the beams. This transverse holographic method of forming gratings proves to be much more efficient and flexible than the previously reported technique. Gratings that are formed in this manner are not length limited by saturation effects[3] and can be tailored to a desired transmission or reflection filter characteristic by shaping and tilting the writing pattern through control of the included angle and divergence of the beams.

A grating is formed by exposing a short length of bare, photosensitive, germanosilicate fiber to a pair of overlapping coherent UV beams. The experimental arrangement is shown in Fig. 1. A tunable excimer-pumped dye laser, operated at a wavelength in the range of 486–500 nm, is used with a frequency-doubling crystal to provide a UV source that lies in the 244-nm band and has an adequate coherence length. The UV radiation is split into two equal-intensity beams and then recombined to produce an interference pattern within the core, normal to the fiber axis. The intensity of the pattern is increased by focusing the beams on the fiber with a pair of cylindrical lenses. The resulting focal spot is approximately rectangular, approximately 4 mm long by 125 μm wide.

A filtered mercury arc source is used with a high-resolution monochromator to measure the reflection and transmission spectra of the grating. The reflected signal is monitored by inserting a beam splitter at the fiber input, and the reflectivity is measured by comparing the reflected signal level to the power reflected, at a wavelength near but out of the filter band, from a mirror placed at the output end of the fiber.

The strongest gratings were written with 244-nm pulsed radiation that had an average power of 4–20 mW. Several different fibers were used, with core diameters of 2.2–2.6 μm and N.A.'s of 0.17–0.24, corresponding to GeO_2 doping of 5–12.5 mol%. Bragg gratings were formed with center wavelengths of 577–591 nm in (i) commercial (Spectran) 6.6-mol % germanosilicate-core, silica-clad fiber; (ii) fiber similar to that used by Hill *et al.*[1,2]; (iii) elliptical-core, polarization-

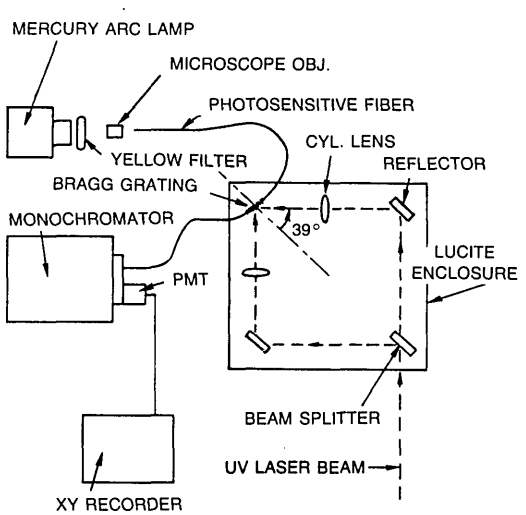

Fig. 1. Diagram of the experimental setup. A beam splitter (not shown) at the fiber input end is used with the monochromator to measure the reflection spectrum of the Bragg grating. PMT, photomultiplier tube.

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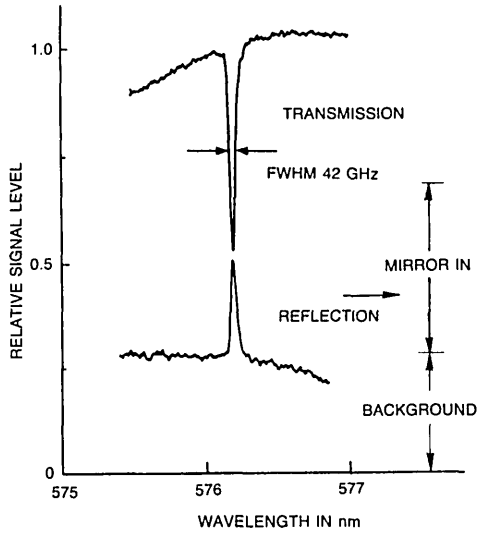

Fig. 2. Transmission and reflection spectra for a 4.4-mm-long Bragg grating filter. A 1-m narrow-band monochromator with a resolution of 0.02 nm was used with a filtered arc lamp source to measure the in-fiber filter characteristics. The measured FWHM is corrected for the monochromator spectral response broadening.

maintaining fiber (Andrew); and (iv) in fiber with a high germania content (N.A. = 0.24) containing a small amount (0.5–1 mol %) of phosphorus.

As the periodic index modulation develops in the fiber core, a narrow notch (or peak) appears in the transmission (reflection) spectrum. The center of the peak or notch occurs at the predicted Bragg wavelength $\lambda = 2n\Lambda$, where Λ is the grating period and n is the mode index. Figure 2 shows the reflection and complementary transmission spectra of a grating formed in a 2.6-μm-diameter core, 6.6-mol % GeO_2-doped fiber after 5-min exposure to a 244-nm interference pattern with an average power of 18.5 mW. The two spectra have similar line shapes and complementary values of transmittance and reflectance. The length of the exposed region is estimated to be between 4.2 and 4.6 mm, as deduced from inspection of a witness burn spot in a paper target. The FWHM of a uniformly exposed region of this length should be about 26 GHz (Refs. 3 and 7); however, the observed linewidth shown in Fig. 2 is 42 GHz, suggesting that the intensity pattern is tapered. The lack of pronounced sidelobes also supports this conclusion.

The gratings are observed to form quickly at power levels of 10 mW and higher. For example, after 10 sec of exposure to an average pulse power of 23 mW the measured transmittance at the center of the Bragg filter decreases to 0.65, and after 30 sec of exposure it decreases to 0.55. Exposure to the UV flux in some fibers causes an immediate broadband drop in transmission, which then gradually recovers. In the 6.6-mol % GeO_2-doped commercial fiber the transmission returned to within 6% of its previous level within 1 min.

Because the spectral width of the grating filter is narrow and the index perturbation extends across the entire core cross section, it can be used to separate the fundamental HE_{11} mode from the higher-order modes. Figure 3 shows the measured transmission spectrum of a slightly multimode fiber. The fiber used in this experiment had a cutoff wavelength of 632 nm, corresponding to a N.A. of 0.22 (11 mol % GeO_2 doping), and a core diameter of 2.2 μm. The Bragg wavelength of the fundamental occurs at 581.5 nm. At this wavelength, the value of the normalized frequency V is 2.62; the fiber just supports the first set of higher-order modes. Under these conditions the separation of phase indices, and therefore the Bragg wavelengths, of the two modes is greatest and the individual peaks in the spectrum are easily resolvable by the in-fiber grating filter. The measured separation is within 10% of the predicted value as computed from the Bragg condition $\lambda_B = 2n\Lambda$ and the dispersion relation for step-index fibers.[8]

The Bragg wavelengths for the principal modes in a polarization-maintaining fiber will also be separated by the difference in their axial wave numbers, or the fiber birefringence. To show this, a weak grating was written in a commercial elliptical-core, germania-doped polarization-maintaining fiber (Andrew). The transmitted line shape, measured without a polarizing filter at the output of the fiber, consisted of the superposition of two lines. By use of a polarizer at the output, these lines could be identified with the principal horizontal and vertical modes of the fibers.

We can estimate the strength of the index perturbation ($\Delta n/n$) by comparing the measured peak reflectivity of a grating of known length L with a prediction of the efficiency of a volume hologram within the core of the fiber.[3,7] It can be shown[3] by solution of the coupled mode equations for the forward- and backward-traveling waves in a fiber containing a Bragg filter that the reflectivity at the Bragg wavelength is given by

$$R = \tanh^2 \Omega, \tag{1}$$

where

$$\Omega = \pi n(L/\lambda)(\Delta n/n)\eta(V). \tag{2}$$

The factor $\eta(V) \simeq 1 - 1/V^2$, $V \geq 2.4$, is the fraction of the integrated fundamental mode intensity contained in the core.

The measured peak reflectivities of two Bragg grating filters, written in different fibers with different

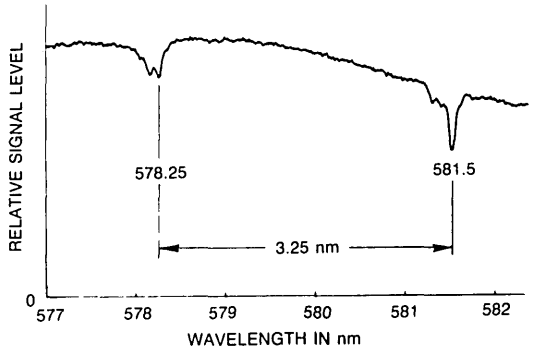

Fig. 3. Transmission spectrum of a Bragg filter in a multimode fiber. The fundamental mode is reflected by ~30% at a wavelength of 581.5 nm. The next set of higher-order modes appears at a wavelength that is 3.25 nm shorter than the notch at the fundamental.

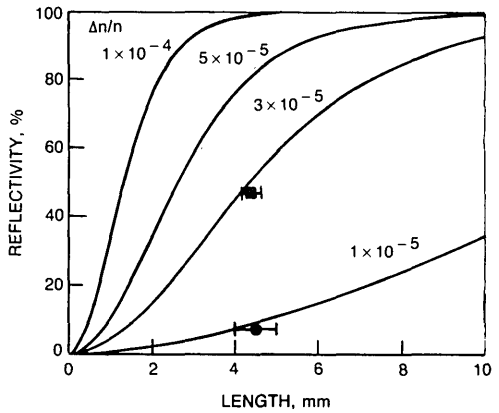

Fig. 4. Computed (solid curves) and measured reflectivity for Bragg gratings of various strengths as a function of length. Experimental points are shown for a grating written with an average power of 18.5 mW at a wavelength of 244 nm (filled square) and with an average power of 4.5 mW at a wavelength of 257.3 nm (filled circle). Two different fibers were used.

power levels, are compared in Fig. 4 with theoretical predictions for gratings of various strengths as a function of the length of the exposed region. The weaker 7% reflectivity filter was written with a UV laser beam at a wavelength of 257.3 nm, just on the edge of the oxygen-vacancy defect absorption band, using pulses from a mode-locked argon-ion laser and a KDP second-harmonic generator. The core was exposed for 20 min to an average power of 4.5 mW. The fiber was similar to those used by Hill *et al.*[1,2] (core diameter 2.2 μm, N.A. = 0.22) in the first experiments on photorefractive effects in germanosilicate fiber. Much stronger gratings of about the same length with reflectivities of 50–55% were written in commercial germanosilicate fiber (core diameter 2.61 μm, N.A. = 0.17) using a 5-min exposure to a pulsed crossed-beam pattern with an average power of 18.5 mW. In this case a dye laser was used with a β-BaB_2O_4 crystal to generate second-harmonic UV radiation at 244 nm, which is close to coinciding with the center of the defect absorption band. Based on the measured reflectivity, the fractional index change is estimated to be $2.8–3 \times 10^{-5}$, assuming a grating of uniform strength. The peak index perturbation could be somewhat larger, however, since the linewidth measurements are wider than expected for a uniform grating.

We can compare the efficiency of writing in-fiber gratings with coherent UV radiation at 244 nm to the two-photon process at 514.5 nm. To obtain an index perturbation of 3×10^{-5} using cw argon-ion radiation at 514.5 nm required a writing power of 90.7 mW with an exposure of approximately 6 min.[3] This is equivalent to exposing the core (diameter of 2.5 μm) to an energy flux of 665 MJ/cm^2. A grating of similar strength is obtained with an energy flux of only 1 kJ/cm^2 at a wavelength of 244 nm by directly bleaching the absorption band, an improvement of 6.7×10^5 in writing efficiency!

The Bragg gratings formed by our holographic technique with 257- or 244-nm radiation appear to be permanent and stable at high temperatures. A grating in the commercial fiber was heated to 500°C and maintained at that temperature for 18 h without a change in its reflectivity or line shape. The only variation was an expected shift in the line center due to the combination of thermal expansion and a change in refractive index with temperature and stress relief.

The mechanism that forms the gratings is not fully understood; all we can say is that it is related to the bleaching of the oxygen-vacancy defect band in germania or germania-doped silica. Normally, germanium is incorporated in the silicate glass in the Ge^{+4} oxidation state, i.e., as GeO_2; however, Ge^{+2} can occur if GeO_2 is dissociated into GeO and O_2 in the formation of the glass, say, during the preparation of a modified chemical-vapor-deposition process preform.[5,6] This process, whereby the reduced Ge^{+2} species is formed, is favored if the processing temperature is raised to 1650°C and the molten glass is cooled quickly.[9] Preliminary measurements of the UV absorption spectra of germanosilicate preforms suggest that the drawing process can cause the Ge^{+2} defect band to form.

In summary, a new method for forming in-fiber Bragg gratings has been demonstrated. The grating is formed in photorefractive germanosilicate fiber by exposure to a coherent two-beam UV interference pattern. This technique provides a new means for making quasi-distributed measurements of temperature and strain by monitoring the shift in the Bragg wavelength of the sensing regions, each being individually tuned to a distinct wavelength, or by forming pairs of independent Fabry–Perot cavities. Possible applications include high-efficiency distributed-feedback reflectors, wavelength-selective couplers and taps, and dispersion-compensating filters.

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