Photosensitization of optical fiber and silica-on-silicon/silica waveguides

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Localized heating with a flame is shown to be a simple and effective method for substantially augmenting the photosensitivity of high-silica optical waveguides to (UV) light. The method increases the photosensitivity of standard (Ge-doped core) telecommunications fiber by a factor greater than 10 (photoinduced $\Delta n_{UV} > 10^{-3}$) and renders strongly photosensitive the cores of high-quality $Ge:SiO_2$-on-Si and $Ge:SiO_2$-on-SiO_2 planar waveguides that were negligibly photosensitive before treatment. We have written large-modulation-depth Bragg gratings, in both fiber and planar optical waveguides photosensitized by our method, using KrF (249-nm) radiation incident upon the waveguides through a zero-order-nulled phase mask. It is noteworthy that photosensitization by our method is achieved with a negligible increase in loss at the three principal optical communication windows.

Optical waveguides can exhibit the property of photosensitivity[1] manifest as a permanent, light-induced refractive-index change. Initial experiments demonstrated the phenomenon in optical fibers, but recently it has been detected as well in planar glass structures, including, for example, silica-on-silicon[2,3] and silica-on-silica[3] planar waveguides.[4–6]

Photosensitivity can be used to make intramode retroreflecting Bragg gratings,[1,7] mode converter gratings,[8,9] and rocking rotators[10] in optical waveguides; to fabricate such devices, a permanent, spatially periodic refractive-index modulation is impressed with light along the length of the photosensitive core of the optical waveguide.

The near-UV absorption spectrum of Ge-doped-core optical fiber and of $Ge:SiO_2$-on-Si or $Ge:SiO_2$-on-SiO_2 waveguide is influenced strongly by the type and concentration of in-core defects. Photosensitivity in Ge-doped core waveguides is linked with absorption that results from oxygen-vacancy defects in the 240-nm UV region.[7] High-quality optical fiber such as Corning SMF-28 fiber and Nippon Telegraph and Telephone silica-on-silicon planar guides contain comparatively low concentrations of defects. As a result, both types of waveguide are relatively transparent in the near UV and are characterized as being weakly photosensitive. To enhance the photosensitive response of such waveguides, defects must be created (predominantly only in the core and not the cladding) that are strongly absorbing at the activating wavelength and that are of the type that lead to photosensitivity. Preferably, the defects should be created only over that length of waveguide to be used to make the device of interest.

In this Letter we describe and characterize an effective and simple method for substantially augmenting the photosensitivity of weakly photosensitive high-silica Ge-doped core optical waveguides to UV light. We note parenthetically that the method may also work for photosensitizing other types of optical waveguide: those doped with Ce or Eu and codoped with alumina, for example. In contrast to other methods,[6] photosensitization in our case is achieved with a negligible increase in loss at the three principle optical communication windows for typical Bragg retroreflector device lengths.

The region of the optical waveguide to be photosensitized is brushed repeatedly by a flame fueled by hydrogen but to which a small amount of oxygen is sometimes added (approximate flame temperature as high as 1700 °C). The photosensitization takes approximately 20 min to complete for maximum effect under the conditions used in our experiments. Because a relatively small flame can be used to brush the waveguide, the method provides highly localized photosensitization.

The flame-brush method has been used to increase the photosensitivity of standard (Ge-doped core)

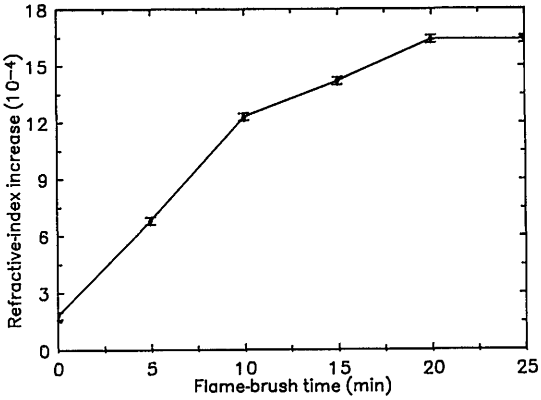

Fig. 1. Plot of the maximum (saturated) photoinduced index change observed in Corning SMF-28 fiber as a function of processing time under the flame brush.

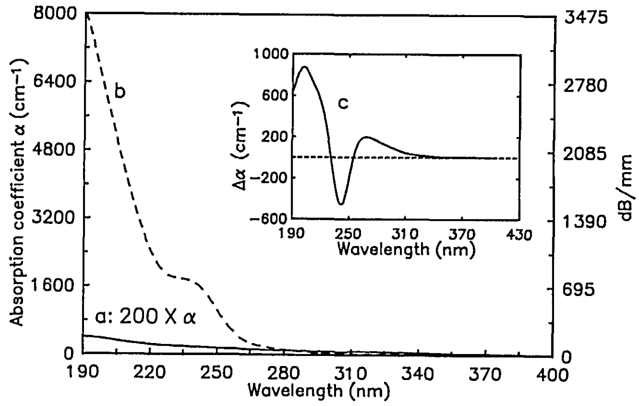

Fig. 2. Absorption coefficient of the substrate and waveguide layer before flame-brush treatment multiplied by 200 (curve a) and of the waveguide layer after flame-brush treatment (curve b). Curve c is the photoinduced change in the absorption coefficient of the flame-photosensitized waveguide layer after exposure to UV light.

telecommunications fiber by a factor greater than 10 (photoinduced $\Delta n_{UV} > 10^{-3}$ at $\lambda = 1540$ nm). Figure 1 is a plot of the maximum (saturated) photoinduced index change observed in Corning SMF-28 fiber as a function of processing time under the flame brush. The UV light exposure conditions used were $\lambda = 249$ nm, fluence 300 mJ/cm^2 per pulse, pulse repetition frequency 50 Hz, exposure time 15 min, and pulse duration 12 ns. In a fiber sample that is not flame brushed we observe a photoinduced waveguide core index change of only 1.6×10^{-4}; after 20 min of flame-brush processing the photoinduced change that is observed in a similar fiber sample peaks at 1.75×10^{-3}.

The flame-brush method also renders strongly photosensitive the waveguide core of our samples of high-quality Ge:SiO$_2$-on-Si channel waveguides and of Ge:SiO$_2$-on-Si-O$_2$ slab waveguides that were negligibly photosensitive before treatment. Experimentally, we observe a larger photosensitization effect in these planar waveguides than we do in the SMF-28 fiber: the small pitch ($\lambda_{\text{Bragg resonance}}/2n_{\text{effective}}$) photoinduced refractive-index modulation that we achieve in the waveguide cores of unprocessed planar waveguides is below our detection threshold, but with flame-brush treatment it becomes somewhat larger than the photoinduced refractive-index modulation in similarly flame-brushed SMF-28 fiber for the same UV exposure conditions.

The planar film waveguides were fabricated by flame hydrolysis deposition of Ge-doped SiO$_2$ onto a silica substrate. The index step, Δn, of the 5-μm-thick Ge-doped layer on the SiO$_2$ was measured at $\lambda = 633$ nm to be $1.14 \pm 0.04 \times 10^{-2}$ before treatment and increased to $1.32 \pm 0.04 \times 10^{-2}$ after 10 min of flame-brush treatment. Associated with this change in refractive index is an increase in the absorption coefficient of the waveguide core in the UV spectral region. Curve a of Fig. 2 is the dispersion in the absorption coefficient of the waveguide layer and the substrate (multiplied by 200) measured normal to the substrate before flame-brush treatment. Curve b is the dispersion in the absorption coefficient for the waveguide layer only, measured after flame-brush treatment (no change is observed in the substrate under the same flame-brush conditions). The great increase in UV absorption of the waveguide layer that results from flame-brush treatment is apparent: approximately 700 dB/mm at 240 nm. Kramers–Kronig causality predicts that an increase in absorption at short wavelengths causes an increase in refractive index at long wavelengths, as we observe. Curve c is an experimental measurement of $\Delta\alpha$, the photoinduced change in the dispersion of the absorption coefficient for the flame-photosensitized waveguide layer, caused by 249-nm UV-light irradiation for 40 min with a fluence of 112 mJ/cm^2 per pulse at a 50-Hz pulse repetion frequency. The effect of the irradiation is to bleach out the absorption at 240 nm and simultaneously to increase it on both sides of the band (at 213 and 281 nm).[11] The result is that UV irradiation increases the net UV absorption of the sample and thus, as observed, increases the refractive index at longer wavelengths.

For comparison, we measured the change in absorption that was due to flame-brush treatment of a homogeneous silica substrate. The substrate was identical to that which we used for the flame hydrolysis deposition of the Ge:SiO$_2$ planar optical waveguide described above. The absorption of the substrate is essentially unaffected by the processing (less than 2% change in absorption at 240 nm). Therefore we attribute the increase in absorption in samples processed by flame brush entirely to the effect of processing on the optical properties of the Ge:SiO$_2$ waveguide layer.

We postulate on this evidence that flame brushing of a waveguide affects preferentially the optical properties of the Ge-doped silica core and leaves unaffected the properties of the cladding. In this sense it is an ideal photosensitization process because the cladding can remain transparent, thereby enabling the activating light to reach the core of the waveguide unattenuated. At the same time, processing creates strong absorption in the Ge-doped core, rendering the core highly photosensitive so that UV light can effect a change in its refractive index.

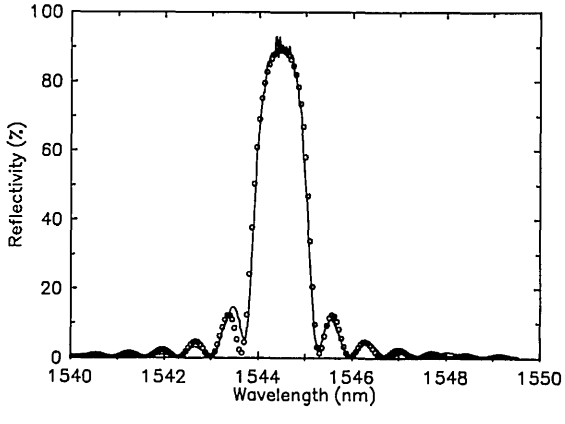

Fig. 3. Lowest-order TM-mode spectral response of a 1.15-mm Bragg grating written in a flame-brushed standard Ge:SiO$_2$-on-Si channel waveguide. The circles are theoretical values for a uniform Bragg grating.

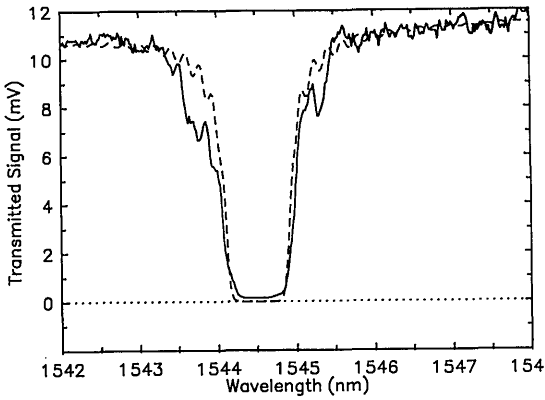

Fig. 4. Measured transmission (solid curve) spectrum of a 4-mm-long Bragg grating in Ge:SiO$_2$-on-Si waveguide. The dashed curve is a theoretical fit to the experimental data with refractive-index modulation depth values obtained from the grating response shown in Fig. 3.

In optical waveguides photosensitized by our method, we have written strong Bragg gratings in channel and fiber-optic waveguides, with KrF (249-nm) radiation incident upon the samples (fluence 400 mJ/cm^2 per pulse) through a zero-order-nulled photolithographic grating phase mask patterned with a pitch required for optical waveguide Bragg resonance at ~1540 nm. We have described elsewhere the use of such a phase mask for writing Bragg gratings.[12] Figure 3 is the measured wavelength response of a 1.15-mm-long Ge:SiO$_2$-on-Si channel waveguide Bragg grating. The 90% reflectively corresponds to a core refractive-index modulation amplitude of 9.5×10^{-4}. The measured response fits closely with the expected theoretical spectral response of a uniform, finite-length Bragg grating. To write the Bragg grating, we photosensitized the waveguide by 10 min of flame-brush processing before irradiation by the KrF excimer laser beam, which was incident upon the waveguide at a 50-Hz pulse repetition frequency for 15 min through the photolithographic grating phase mask. The writing of Bragg gratings is useful for characterizing the photosensitive response of optical waveguides. We can monitor both the average change in index with exposure and the corresponding depth of modulation of the index. The shift of the Bragg resonance wavelength as a function of photolithographic exposure dose to UV light provides a measure in real time of the average change in the refractive index caused by the exposure. The strength of the Bragg resonance yields the depth of the photoinduced spatial modulation. With phase mask photolithography on fiber, the ratio of the modulation to the average index change that we attain consistently is ~0.4. At high fluence-per-pulse levels (>250 mJ/cm^2 per pulse), we simultaneously write a high-quality surface relief grating at the silicon–silica interface of our planar waveguides. We believe that these surface relief gratings result from light-induced melting of the silicon together with stress relaxation at the interface. Such stress relaxation also affects the average photoinduced index change that is observed in these waveguides.

We carried out temperature stability measurements on a photoinduced Bragg grating whose response was similar to that shown in Fig. 3. After the sample was held at 500 °C for 17 h, the refractive-index modulation decreased to 40% of its original value.

We have also fabricated longer-length (4-mm) Bragg reflectors in photosensitized Ge:SiO$_2$-on-Si channel optical waveguides. Figure 4 shows the transmission spectrum of the Bragg grating. The minimum in the transmission curve corresponds to a peak Bragg grating reflectivity of 99%. The dashed curve is a theoretical response with a modulation of 9.5×10^{-4} as obtained for the 1.15-mm grating with the same exposure conditions. The photosensitization conditions in the two cases were also the same. The peak reflectivity that is calculated is greater that 99.9%. We attribute the lower measured reflectivity to the channel waveguide's being multimode.

Photosensitized waveguides could simplify single-pulse writing of in-fiber Bragg gratings[13] and yield useful devices.

In conclusion, we have demonstrated an effective method for photosensitizing optical waveguides with high spatial selectivity (only the selected portion of the waveguide need be photosensitized) and used the method for fabricating efficient Bragg gratings in Ge:SiO$_2$-on-Si and Ge-doped-core optical fiber waveguides.

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