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Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask

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A photolithographic method is described for fabricating refractive index Bragg gratings in photosensitive optical fiber by using a special phase mask grating made of silica glass. A KrF excimer laser beam (249 nm) at normal incidence is modulated spatially by the phase mask grating. The diffracted light, which forms a periodic, high-contrast intensity pattern with half the phase mask grating pitch, photoimprints a refractive index modulation into the core of photosensitive fiber placed behind, in proximity, and parallel, to the mask; the phase mask grating striations are oriented normal to the fiber axis. This method of fabricating in-fiber Bragg gratings is flexible, simple to use, results in reduced mechanical sensitivity of the grating writing apparatus and is functional even with low spatial and temporal coherence laser sources.

Certain optical fiber waveguides exhibit the property of photosensitivity[1] which is a practical means for photoinducing permanent refractive index changes in the core of those fibers. Photosensitivity is not restricted to fiber structures: it has also been detected in several types of planar glass structures, including, for example, silica-on-silicon[2,3] and silica-on-silica[3] planar waveguide devices.[4,5]

Current interest in photosensitivity is directed to the fabrication of optical waveguide devices such as intramode retroreflecting Bragg gratings,[1,6] mode convertor gratings,[7,8] and rocking rotators.[9] The general approach for making these devices is to photoinduce in the photosensitive core of the optical waveguide a refractive index grating. At the resonant wavelength of the structure, phase-matched, efficient, power exchange between grating-coupled modes is possible.

There are two basic methods for photoinducing gratings in photosensitive optical fiber waveguides: either by internal or external writing. Internal writing is a holographic process where the modes to be coupled are launched as coherent bound modes of the waveguide and allowed to modify by a two-photon absorption process the refractive index of the waveguide core[10] (i.e., form the hologram). Subsequent launching of one mode reconstructs the other. External writing can be accomplished point-by-point[8,9] for mode convertor gratings, or using the holographic interference of two coherent UV beams[6] for Bragg retroreflectors.

In this letter, we describe a nonholographic method for writing Bragg retroreflectors, in photosensitive optical fiber or planar waveguide structures. The essence of the method is to fabricate a phase mask grating that can be used to modulate spatially with pitch $\lambda_{\mathrm{Bragg}}/n_{\mathrm{effective}}$ the phase of a UV beam (for example, from an excimer laser source); λ_{Bragg} is the desired resonant wavelength for retroreflective intramode coupling in the fiber and $n_{\mathrm{effective}}$ is the effective index of the coupled modes at λ_{Bragg}.

The phase mask grating is used in a precision photolithographic apparatus and is placed in contact, or near-contact, with the optical fiber, its grating striations directed (usually) normal to the fiber axis. The UV beam [a KrF excimer laser beam (249 nm) in our case] at normal incidence passes through the mask, is phase modulated spatially and diffracted to form an interference pattern laterally (Bragg grating pitch) and along the incident laser beam direction (Talbot pitch) as illustrated in Fig. 1. The interference pattern photoimprints a refractive index modulation (Bragg grating) in the photosensitive fiber immediately behind the phase mask.

The phase mask grating consists of a one-dimensional surface-relief structure fabricated in a high quality fused silica flat transparent to the KrF excimer laser radiation. The shape of the periodic surface-relief pattern of the phase mask approximates a square wave in profile, as shown in the Fig. 1. The amplitude of the periodic surface-relief pattern is chosen to modulate by π radians the phase of a KrF excimer laser beam, i.e., $4\pi(n_{\mathrm{silica}}-1)A/\lambda_{\mathrm{KrF}}=\pi$, where A is the amplitude of the surface-relief pattern. This choice of the surface-relief grating amplitude results in a grating diffraction pattern for the design wavelength with nulled zero-order diffracted (through) beam. In practice, the zero-order beam can be suppressed to less than 5% of the light diffracted by the mask. The principal beams exiting our mask are the diverging plus-one and minus-one orders each of which contain typically more than 35% of the diffracted light.

The mask need not be shaped to a square wave. For example, Goodman[11] discusses zero-order nulled surface-relief phase masks gratings shaped to a sinusoid that would be equally useful in our application.

It is worth noting that the principal period $\lambda_{\mathrm{Bragg}}/2n_{\mathrm{effective}}$ of the mask's diffraction pattern is independent of wavelength. Therefore, in principle, it is possible to write a Bragg grating through the mask with a collimated broadband source.

In order to test the performance of the photolithographic apparatus, we selected two optical fibers known to be highly photosensitive. The first was an Andrew Corporation standard D-type polarization-maintaining fiber optimized for 1300 nm (cutoff = 960 nm, beat length $L_B=1.02$ cm at 1292 nm, core/cladding $\Delta n=0.031$ and elliptical core size 1.5×3 μm) but which nonetheless exhibits suffi-

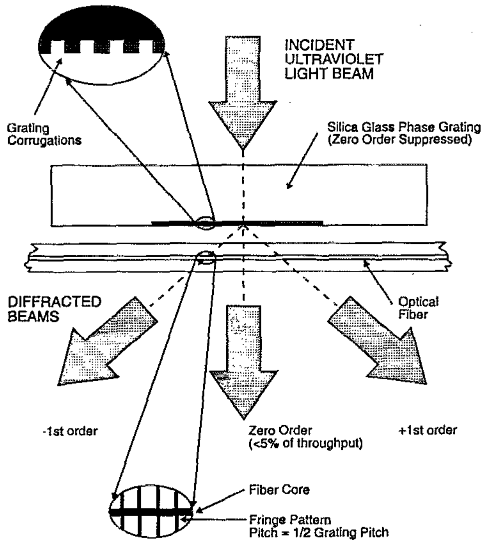

FIG. 1. Schematic of photolithographic apparatus for photoimprinting a refractive index Bragg grating in a photosenstive optical fiber waveguide.

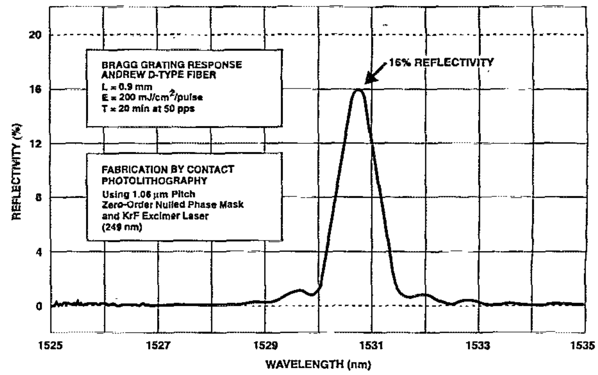

FIG. 2. Spectral response of a Bragg grating fabricated with a UV laser source and phase mask photolithography.

ciently low loss at the Bragg resonant wavelength of 1531 nm that we use in our experiments. This fiber has a core that is highly doped with germanium in comparison to standard telecommunications fiber; germanium-doped fibers are photosensitive.[12,13] In particular, Andrew *D*-type fiber has been reported to be strongly photosensitive (we measure unsaturated photoinduced refractive index changes the order of 6×10^{-4}), probably due to its relatively high germanium dopant concentration.[6] The second fiber was supplied by AT&T Bell Laboratories and is known to be strongly photosensitive.

The UV source we use for Bragg grating photolithography is an unmodified Lumonics excimer laser operated at 249 nm, beam cross-section 0.7×2 cm^2, pulse duration 12 ns and 50 Hz pulse repetition rate. The unfocused energy density per pulse is 100 mJ per cm^2. When no provision is made either to injection-lock or to filter spatially the beam, such a laser produces a low coherence output. The only optimization we undertake in preparation for photoimprinting a Bragg grating is to place the phase mask grating with striations parallel to the long dimension of the beam cross section, because we determined experimentally that spatial coherence is better for this orientation than for orthogonal placement.

Writing with low coherence beams is an important test of the performance of the photolithographic Bragg grating photoimprinting apparatus. The purpose of Bragg grating photolithography is to open access to parallel device fabrication techniques, to permit the use of proven, high-fluence, industrial laser sources and to simplify manufacturing alignment procedures.

The phase grating that we use in the photoimprinting apparatus was developed by Lasiris Inc. It is a surface-relief device manufactured on a high optical quality fused silica flat. The period of the grating is approximately 1060 nm; the 249 nm zero-order diffracted beam is nulled below 5%, and 37% of transmitted light is contained by each of the plus- and minus-one order diffracted beams. The grating measures 1 mm square. The period of the Bragg grating photoimprinted with the flat is 530 nm resulting is an estimated high-fused silica waveguide (refractive index $=1.46$) Bragg resonance wavelength of $530\times2\times1.46$ $=1547$ nm. We observed resonance experimentally at 1531 nm (see Fig. 2).

Figure 2 illustrates the spectral response of a Bragg grating photoimprinted though the Lasiris phase mask into the Andrew Corp. *D*-type fiber. Mild focusing of the excimer laser beam, using a cyclindrical lens aligned with cylinder axis parallel to the fiber, increased the fluence level per pulse used for Bragg grating photoimprinting from 100 to 200 mJ per cm^2. The 249 nm KrF excimer laser was pulsed at 50 Hz for 20 min during fiber exposure. A peak reflectivity of 16% was achieved in a grating estimated to be approximately 0.95 mm long (calculated assuming a uniform in-fiber grating, the 0.85 nm spectral width of the response, the 530 nm pitch of the Bragg grating, and the 1531 nm Bragg resonance wavelength). The sidebands in the spectral response are clearly visible, suggesting that the grating is substantially uniform along its entire length. From the grating reflectivity data we calculate (in the tightly bound mode limit) the amplitude for the refractive index modulation to be 2.2×10^{-4}. This value compares favorably with the average refractive index change which we determine to be 6×10^{-4} from the shift in Bragg grating resonance due to photoexposure and knowledge of the fiber's effective index dispersion at 1531 nm. Ideally, we expect the apparent modulation depth to be the same or larger than the average index change when we expose fibers to maximum-contrast grating-diffraction patterns. The depth-to-average index change ratio is influenced by the following intrinsic factors: nonlinearities in the photosensitive response of the fiber, the less-than-perfect nulling of the zero-order beam, the presence of higher order diffracted beams downstream from the mask and the low coherence of the laser source. It is also influenced by fiber/mask alignment during fabrication.

Our Lasiris phase masks have been found to tolerate fluence levels per pulse of 1 J per cm^2 without damage. Using this fluence level per pulse we photoimprinted a

Bragg grating with 35% reflectivity in the AT&T fiber after a 5 min 50 Hz exposure.

In general, Bragg grating reflectivity increases rapidly at the beginning of the exposure process and subsequently saturates at a value related to incident fluence per pulse levels. An increase in fluence per pulse increases, to some limit, the saturated reflectivity of the ensuing Bragg grating. However, above a certain fluence, a peak in reflectivity develops at some value of photoexposure. For greater photoexposures a decrease in reflectivity obtains and at the same time the shape of the wavelength response of the Bragg grating changes significantly, developing, for example, a notch at the center wavelength of the response. We do not understand the origin of the spectral response changes.

Because the masks are fabricated under computer control, photolithographic imprinting through a phase mask offers much flexibility for varying the pitch and the strength of the Bragg grating coupling coefficient, $\kappa(z)$, as a function of distance z along the waveguide axis; therefore the synthesis of useful Bragg spectral response characteristics should be possible.

In conclusion, we have reported a simple method for fabricating high quality Bragg gratings in photosensitive optical waveguides, using low coherence lasers suitable for industrial environments. The spatial phase masks in the photolithographic Bragg grating imprinting apparatus apparently do not sustain damage in use. The combination of phase mask photoimprinting with single-pulse writing of in-fiber Bragg gratings[14] could yield high-performance, low-cost devices.

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