Single-excimer-pulse writing of fiber gratings by use of a zero-order nulled phase mask: grating spectral response and visualization of index perturbations

B. Malo, D. C. Johnson, F. Bilodeau, J. Albert, and K. O. Hill

Communications Research Center, P.O. Box 11490, Station H, Ottawa, Ontario K2H 8S2, Canada

Received March 22, 1993

Optical fiber Bragg reflectors have been written by irradiating the fiber from the side through a phase mask with a single pulse of high-power 249-nm excimer-laser light. Efficient tapping of light to the radiation modes has been achieved for light at wavelengths shorter than the Bragg wavelength. The photoinduced periodic refractive-index perturbations have been observed directly with an optical microscope and are shown to have the same period as the phase mask and to be highly localized on one side, the irradiated side of the fiber core–cladding boundary.

Recently it has been demonstrated that fiber Bragg gratings can be photoimprinted in the core of an optical fiber by irradiating the fiber from the side with ultraviolet light that passes through a silica glass phase mask.[1,2] In comparison with earlier fiber grating writing techniques,[3–5] the use of a phase mask simplifies significantly the optical apparatus needed to write the Bragg reflectors. The mask is compact, is easy to align, has reduced sensitivity to mechanical vibrations, and does not noticeably degrade on exposure to high-power ultraviolet light. Furthermore the temporal coherence requirements on the irradiating light are reduced, thereby permitting the use of a low-cost KrF excimer laser as the writing light source. The first application of KrF excimer lasers in fiber grating writing was by Hill *et al.*[5] to write point by point the index perturbations of a fiber mode converter grating. The application of the KrF excimer laser to write Bragg reflectors with the external holographic writing technique[4] was not feasible, because the coherence of this laser light source was too low. With a phase mask, however, the same low-coherence KrF excimer-laser source can be used to write fiber Bragg reflectors, thus eliminating the need for expensive, frequency-doubled, XeCl excimer-laser-pumped dye-laser systems or line-narrowed injection-locked KrF excimer systems.

These advantages of phase masks suggest their application for writing gratings in fibers by use of a single pulse from an KrF excimer laser. The motivation for single-pulse writing of Bragg reflectors is that the gratings can be photoimprinted in the optical fiber as it is being drawn from a preform, leading to low-cost devices. Such a process may also be useful as a means of fiber marking for identification purposes.

The writing of a Bragg fiber grating by a single excimer light pulse has been demonstrated already.[6,7] The light source used in these experiments is a line-narrowed injection-locked KrF excimer laser, which ensures the spatial and temporal coherence needed in the external holographic writing technique.[4] In this Letter we demonstrate the use of a phase mask for writing fiber gratings with a single pulse from a Lumonix EX-510 KrF excimer laser, and we report on the characteristics of the resulting photoimprinted fiber gratings.

The experimental setup used for writing fiber gratings with a phase mask is described in Ref. 1. The phase mask used in this research is made from high-quality fused-silica glass and has a square-wave surface corrugation with a period $\Lambda = 1060$ nm. Ultraviolet light passing through the phase mask is diffracted into several different orders. Our mask is designed to suppress the amount of light that is diffracted into the zeroth-order beam (<5% at 249 nm). Thus most of the diffracted light (~80%) is contained in the ±1-order diffracted beams.

The essential difference between the experiments reported in this Letter and those described in Ref. 1 is that the fiber in the current work is exposed to a single excimer-laser pulse at a fluence level of approximately 1 J/cm^2, whereas in Ref. 1 the gratings were fabricated by irradiating the optical fiber with excimer-laser pulses at 50 pulses/s for 5 to 20 min at fluence levels ranging from 100 to 500 mJ/cm^2. With the low-fluence multiple-pulse exposure conditions, the photoimprinted Bragg gratings have a period $\Lambda/2$ and thus reflect light in first order at a Bragg wavelength given by $\lambda_{\mathrm{Bragg}} = 2n_{\mathrm{eff}}(\Lambda/2)$, where n_{eff} is the effective refractive index of light in the optical fiber mode at the Bragg wavelength. In contrast, the single-pulse exposure conditions result in gratings with a period Λ and have significantly different reflection and transmission characteristics. This result is consistent with the recent report by Reekie *et al.*[8] that a different mechanism for photosensitivity is occurring during the formation of gratings produced with a single high-power light pulse.

In this research, we photoimprint the Bragg reflectors by placing the phase grating in close proximity to a section of bare optical fiber. We use Andrew Corporation D-type polarization-maintaining fiber, which has a cutoff wavelength of 1200 nm, a beat length $L_B = 7$ mm at 1300 nm, a core–cladding

0146-9592/93/151277-03$6.00/0

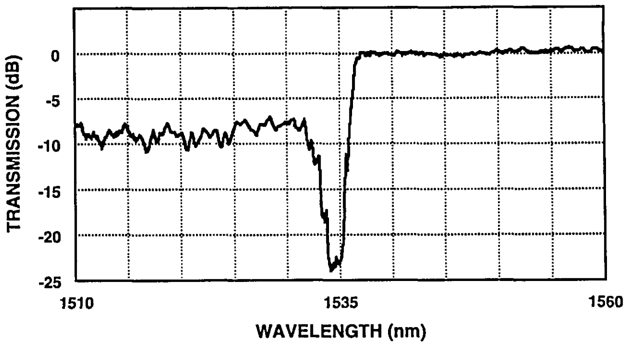

Fig. 1. Transmission spectrum of a Bragg reflector with a peak reflectivity of 99.5%.

$\Delta n = 0.031$, and an elliptical core with dimensions $2\ \mu m \times 4\ \mu m$. The phase grating is placed such that the corrugations in the silica slab are adjacent to the curved side of the D-fiber cladding with the long axis of the corrugations oriented perpendicular to the axis of the optical fiber. Light from the excimer laser is directed normal to the flat surface of the phase grating and passes through. The diffracted beams interfere to form a fringe pattern that photoimprints the Bragg reflector. All gratings reported here have a length of 4 mm and are photoimprinted by a single pulse of 249-nm light from the excimer laser having an irradiation fluence of ~1 J/cm^2 on the cladding of the optical fiber.

Figure 1 shows the transmission response of a 4-mm-long Bragg reflector written in the D-type fiber. For wavelengths longer than 1535 nm, the fiber has 100% transmission. At 1535 nm, a sharp dip in transmission occurs as a result of light reflection by the Bragg reflector (peak reflectivity 99.5% at $\lambda_{Bragg} = 1535$ nm). The FWHM of the reflection peak is 3.5 nm, which is much broader than the spectral width of 0.5 nm expected for a uniform Bragg grating of length 4 mm. For wavelengths shorter than 1535 nm, the single-pulse Bragg reflector transmits only 20% of the light in the measured range. The Bragg grating acts as an efficient tap (80%) for coupling out of the optical fiber, light at wavelengths shorter than the Bragg wavelength. The reflection and transmission spectra obtained for this photoimprinted Bragg reflector are typical of Bragg gratings that do not extend uniformly across the core of the optical fiber. Similar spectra have been obtained for Bragg gratings that are formed by etching a surface relief grating on the core–cladding boundary of the optical fiber.[9] The light lost (i.e., tapped out in transmission by the Bragg reflector) for wavelengths shorter than the Bragg resonance is attributed to the grating's providing phase-matched coupling of the reflected light into the cladding and radiation modes of the fiber.

The transmission response of the photoimprinted Bragg reflector is sensitive to the fluence level of the UV light incidence upon the optical fiber. Photoimprinted gratings are not detected (reflectivity <5%) in fibers irradiated with a single 249-nm light pulse having a fluence level 20% below 1 J/cm^2. Figure 2 shows the response curve of a Bragg reflector that was photoimprinted with a fluence level that is slightly lower (amount of decrease was not accurately measured) than the fluence level used in fabricating the Bragg reflector whose spectrum is shown in Fig. 1. The reduction in fluence level decreases both the Bragg peak reflectivity (~80% at $\lambda_{Bragg} = 1534.2$ nm) and the spectral width (FWHM = 1.0 nm). The light loss at shorter wavelengths is not present in the spectral region shown in Fig. 2 but is shown in Fig. 3, which is a transmission spectrum of the same photoimprinted Bragg reflector over a larger spectral range. The radiative loss extends from ~1500 nm to beyond 600 nm and increases from 20% at 1500 nm to over 80% at 600 nm.

A new feature in the transmission spectrum shown in Fig. 3 is the sequence of sharp transmission dips that occur at 1535, 1030, 770, and 620 nm. The light at these wavelengths is not radiated but is reflected back into the bound modes of the fiber. Since a grating with period $\Lambda/2$ cannot efficiently reflect light at wavelengths of 1030 and 620 nm, we attribute all the reflections to a photoimprinted grating that has a period Λ, equal to the period of the phase mask. Assuming the existence of this grating, the condition for resonance is expressed as $m\lambda_{resonance} = 3070$, where $m = 1, 2, 3, 4, 5\ldots$ is the order of the reflection. The constant 3070 is obtained by taking the reflection at 1535 nm to be a second-order reflection ($m = 2$) from the grating. The effective

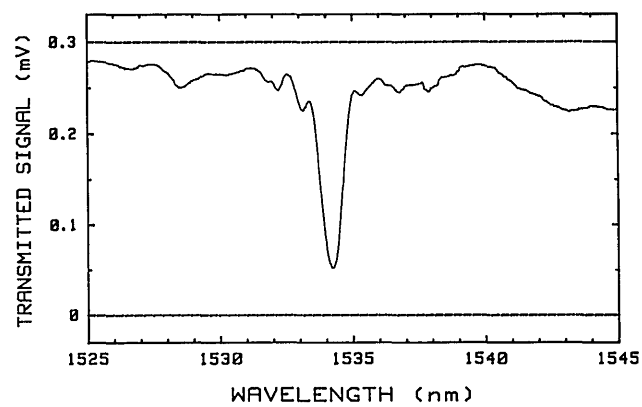

Fig. 2. Transmission spectrum of a Bragg reflector with a peak reflectivity of 80% in spectral region 1525 to 1545 nm.

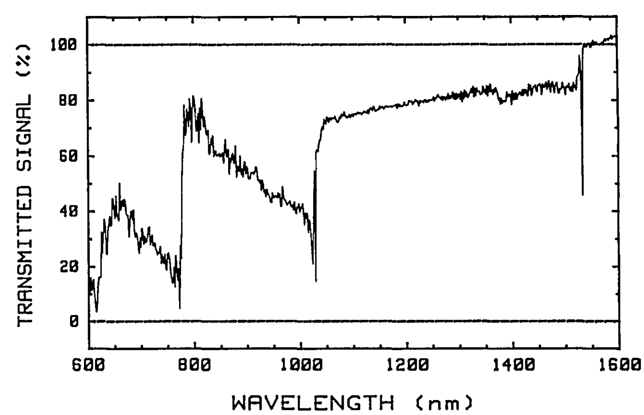

Fig. 3. Transmission spectrum of the Bragg reflector as in Fig. 2 extended over the spectral range 600 to 1600 nm but with a lower resolution than in Fig. 2.

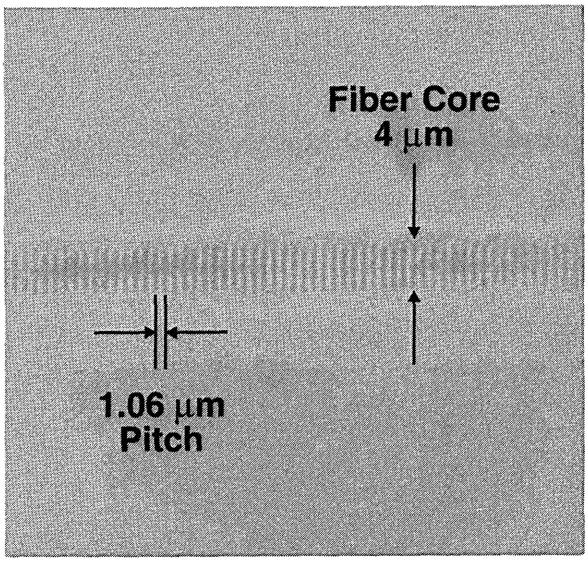

Fig. 4. Photographic image of photoinduced perturbations (dark parallel fringes) as seen through an optical microscope. Spacing between lines in image corresponds to the 1060-nm period of the phase grating.

index n_{eff} for light at 1535 nm is then given by $n_{eff} = 1535/\Lambda = 1.44$. Assuming that the light at the other resonant wavelengths has the same effective refractive index as at the 1535-nm wavelength and taking $m = 1, 2, 3, 4, 5, \ldots$, we obtain the series $\lambda_{resonance} = 3070$, 1535, 1023, 768, 614 nm, which corresponds closely with observation, except that the resonance at 3070 nm is not observable because of the high absorption of glass at this wavelength.

Using an optical microscope, we have been able to verify directly the existence of the Λ period grating by observing the image of the photoinduced perturbation produced by a single pulse of high intensity 249-nm light in the Andrew D-fiber. The image (see the photograph in Fig. 4) appears like a fringe pattern with the 1060-nm period of the phase mask. The high contrast in the fringe pattern suggests that a large photoinduced index change is obtained. The irregularity in the borders of the perturbation pattern indicates that diffusion or melting, and consequently a high temperature, obtains during the photoimprinting process. We have also observed the photoinduced perturbations from the side, i.e., normal to the irradiating direction. The photoinduced perturbations are highly localized on the core–cladding boundary and do not extend across the core of the fiber. The fact that we do not observe a photoinduced perturbation with a period of $\Lambda/2$ does not preclude the existence of a weak grating with this period since the spatial resolution of our microscope viewing system is near its limit.

In summary, we have used a single high-power light pulse from an excimer laser in conjunction with a phase mask to photoimprint Bragg reflectors in optical fibers. The transmission and reflection characteristics of the photoimprinted gratings are significantly different from those photoimprinted at lower intensities. The Bragg reflector functions as an efficient optical tap for light at wavelengths shorter than the Bragg wavelength. The photoinduced perturbations are localized on the core–cladding boundary and do not extend across the core of the optical fiber. These results corroborate those in Ref. 9, where a different grating formation process is postulated to occur at the high intensities used in producing gratings in the single high-power light-pulse regime.

References

1. K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, Appl. Phys. Lett. **62**, 1035 (1993).
2. K. O. Hill, F. Bilodeau, B. Malo, J. Albert, D. C. Johnson, Y. Hibino, M. Abe, and M. Kawachi, in *Optical Fiber Communications Conference,* Vol. 4 of 1993 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1993), paper PD-15, pp. 64–67.
3. K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, Appl. Phys. Lett. **32,** 647 (1978).
4. G. Meltz, W. W. Morey, and W. H. Glenn, Opt. Lett. **14,** 823 (1989).
5. K. O. Hill, F. Bilodeau, B. Malo, D. C. Johnson, and I. Skinner, Electron. Lett. **26,** 1270 (1990).
6. C. G. Askins, T.-E. Tsai, G. M. Williams, M. A. Putman, M. Bashkansky, and E. J. Friebele, Opt. Lett. **17,** 833 (1992).
7. J.-L. Archambault, L. Reekie, and P. St. J. Russell, Electron. Lett. **29,** 28 (1993).
8. L. Reekie, J.-L. Archambault, and P. St. J. Russell, in *Optical Fiber Communications Conference,* Vol. 4 of 1993 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1993), paper PD-14, pp. 60–63.
9. I. Bennion, D. C. J. Reid, C. J. Rowe, and W. J. Stewart, Electron. Lett. **22,** 341 (1986).