Bragg Gratings Made With a Femtosecond Laser in Heavily Doped Er–Yb Phosphate Glass Fiber

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***Abstract*—Bragg gratings made in heavily doped phosphate glass fibers using ultrafast infrared radiation and a phase mask are reported. Refractive indexes $>1.5 \times 10^{-3}$ were induced in Er–Yb-doped phosphate fiber in a few seconds of exposure corresponding to reflectivity above 99.99% for a 6-mm-long grating. Annealing test up to 400 °C shows good thermal stability of the grating structure.**

***Index Terms*—Bragg gratings, fiber lasers, phosphate glass, ultrafast optics.**

I. Introduction

DUE TO their compactness and superior performance, fiber lasers are now becoming important laser systems. The ability to deliver single-mode single polarization beams confined to the small core area with high beam quality makes the fiber laser a suitable candidate for a large range of applications.

The most advantageous way to create the fiber laser cavity mirrors is to directly imprint high reflectivity fiber Bragg gratings (FBGs) into the high gain optical fiber. To date, the writing of in-line FBGs as cavity mirrors was performed mainly in ultraviolet (UV) photosensitive germanium (Ge)-doped silica fibers. Unfortunately, the Ge-doped fiber is characterized by severe ion clustering that results in low laser efficiency and instability. Complicated fiber designs are required in order the avoid Ge doping of the active medium [1].

There are substrate glass materials other than silica that are more suitable for high active dopant concentration, such as phosphate glass. Phosphate glass fibers are an attractive laser medium since they allow for very high levels of rare-earth ion doping and, therefore, high gain coefficients in the fiber core. Erbium ions (Er^{+}) in phosphate glasses are not affected by clustering and quenching and are subjected to low up-conversion losses [2].

The splicing of phosphate glass fiber to silica fiber is difficult, however, resulting in high losses due to physical dissimilarities between the two fibers. Splicing FBGs written in silica fiber to the phosphate active fiber will introduce laser cavity losses. Until recently, it was believed that phosphate glass is generally not photosensitive to UV radiation with only 10^{-5} refractive index variation induced into the glass matrix [3]. An order of magnitude larger refractive index variation (10^{-4}) was obtained in silver-doped phosphate glass [3].

Surprisingly, however, 10^{-4} refractive index variation was reported recently in non-active phosphate fibers without Ag doping. The authors speculated that the high photonic energy 193-nm UV radiation strains the bonds of the glass network generating heat causing structural rearrangements [4].

FBG inscription with femtosecond pulsed 800-nm radiation and a phase mask [5] has proven to be a highly flexible technique for grating inscription in a wide variety of glass materials. Based on the multiphotonic interaction of the interference field generated by the phase mask with the optical substrate, Bragg gratings have been successfully inscribed in lithium niobate and borosilicate waveguides, pure silica fibers, sapphire fibers, and fluoride fibers [6]. Using the point-by-point and phase mask techniques, gratings have also been written in erbium-doped silica fibers with ultrafast infrared (IR) lasers [7], [8].

Recently, waveguide inscription via induced index change in phosphate glass using tightly focused femtosecond IR radiation was demonstrated [9]; however, no Bragg gratings made using ultrafast IR radiation in phosphate waveguides or fibers have been reported to date. It is also important to study how high levels of erbium–ytterbium (Er–Yb) doping affect the interaction between the ultrafast radiation and the phosphate substrate.

In this work, the fabrication of very strong FBGs written in heavily Er–Yb-doped phosphate glass fibers using the IR ultrafast radiation and the phase mask method is reported.

II. Experiment

Phosphate glass fibers with 6-μm core and 125-μm cladding diameters supplied by INO were doped with Er^{3+}–Yb^{3+} levels (Er^{3+}: 1.1 wt%; Yb^{3+}: 11.1 wt%) such that the core glass absorption at 975 and 1535 nm were 6300 and 390 dB/m, respectively. The numerical aperture of the fiber is 0.19–0.20. The fibers were cleaved and polished into 10-cm lengths.

The fibers were exposed to 120-fs 800-nm radiation from a Spitfire regenerative amplifier from Spectra Physics. A schematic of the grating inscription setup is presented elsewhere [10]. The radiation was focused with a 30-mm focal length cylindrical lens through a 3.18-μm pitched phase mask into the center of the phosphate fiber, which was placed 3 mm behind the phase mask in order to interfere only the ± 1 mask orders [10] and produce FBGs with periods of 1.59 μm that are half that of the phase mask and observable under an optical microscope. The 6.4-mm Gaussian laser beam was focused to $\sim$10-μm line focus that was scanned across the fiber core in a $\pm$10-μm span in order to ensure a good overlap of the 6-mm-long FBG with the fiber core. The phosphate fibers were butt-coupled to connectorized SMF-28 pigtails and the

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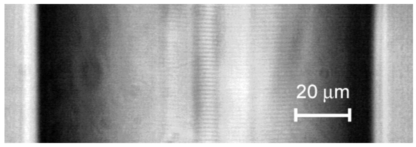

Fig. 1. Third-order 1.59-μm pitched FBG made with IR femtosecond radiation in the core and cladding of the phosphate glass fiber.

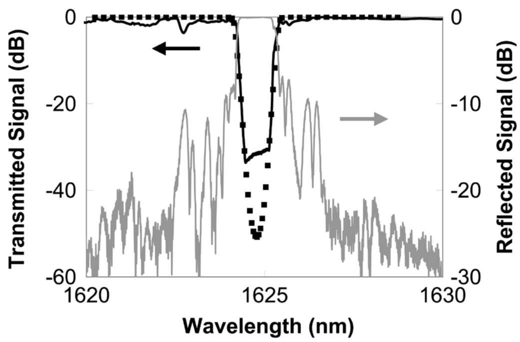

Fig. 2. Transmission (black) and reflection (gray) spectral plots of a grating made with 1000-μJ/pulse IR radiation. The simulation of a 6.4-mm-long grating with a Gaussian profile and $\Delta n = 1.5 \times 10^{-3}$ is superposed on the measured transmission plot (dotted line).

transmission/reflection spectra were measured with a tunable laser source and an optical circulator.

The gratings were probed with an L-band tunable laser and a fast detector with a spectral resolution of 5 pm. The annealing tests were performed in a micro-oven, 40 mm long with embedded heating resistors. The micro-oven was calibrated up to 600 °C using a thermocouple and ultrafast IR laser written Bragg gratings in SMF-28 fiber.

III. Results and Discussion

The phosphate glass fibers were irradiated with IR ultrafast pulse energies starting from 400 μJ/pulse with a repetition rate of 100 Hz. No reflected signal was detected using laser pulse energies$<$600 μJ. At 700 μJ/pulse, a grating structure was visible using an optical microscope.

Strong gratings made with 1000 μJ/pulse for a 60-s exposure are shown in Fig. 1, with the spectral responses of the grating shown in Fig. 2. Based on the Bragg wavelength, the effective refractive index of the phosphate glass fiber was evaluated at 1.533. The spectrum is limited in transmission by the ~30-dB dynamic range of the measurement system in the 1600-nm range. By monitoring the insertion loss variation during grating inscription, the out-of-band loss 5 nm away from the Bragg resonance on the long wavelength side was evaluated to be $<$0.1 dB. A simulation made for a uniform first-order Bragg grating with a 6.4-mm Gaussian apodization profile, presuming a sinusoidal variation of the refractive index modulation Δn that fits the reflection spectrum, corresponds to a Δn of $\sim 1.5 \times 10^{-3}$. Since the grating pitch in the fiber generates a third-order resonance, the 1.5×10^{-3} value of the Δn is in reality an evaluation of the third Fourier component and therefore under estimates the total amplitude of Δn.

Comparative tests made in Ge-doped silica fiber for similar exposure conditions show a much faster growth of the grating

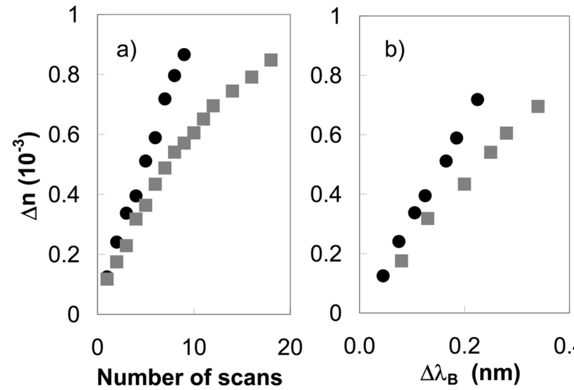

Fig. 3. Growth dynamics of Δn versus (a) number of sweeps of the laser beam and (b) the wavelength shift $\Delta\lambda_B$ of the phosphate grating (black dots) and silica grating (gray squares) under the same writing conditions (1000 μJ/pulse, 50 Hz).

reflectivity in the case of the first-order phase mask compared to that of the third-order phase mask, suggesting that the first-order Fourier component is larger by a factor of three than the third-order Fourier component of theΔn for the third-order gratings. There are, however, differences between the behaviors of the gratings made in silica fiber and phosphate glass fiber. The results presented in Fig. 3(a) suggest that for the same writing conditions, the phosphate grating structure grew faster than the silica grating.

The growth of the grating reflectivity was evaluated at 1000 μJ/pulse and 50-Hz pulse rate. The spectra were measured at the end of each 10-s scan of the fiber core by the focused beam. The core exposure per scan corresponds to ~150 overlapped laser pulses. It is not clear if the higher photosensitivity of the phosphate glass fiber is due to the host glass itself or the high Er–Yb content. The structure of the grating seen in Fig. 1 indicates that the grating is stronger in the core region and, therefore, the active dopant may increase the photosensitivity. In the case of silica fiber, there is no visual difference between the core and the cladding grating [11].

Differences in the characteristic curve of Δn versus the wavelength shift of the Bragg resonance $\Delta\lambda_B$ for gratings written in the phosphate fiber and Ge-doped silica fiber are presented in Fig. 3(b). The data were obtained using identical phase mask and exposure conditions. The different Δn versus $\Delta\lambda_B$ curves are either due to a different mode propagation behavior of the two fibers or due to different interaction of the IR radiation with the phosphate and Ge-doped silica glass, respectively.

Femtosecond IR laser fabrication of waveguides in phosphate glass with fringeless exposures indicated that a region of negative refractive index change occurred in the region exposed to the laser beam [9]. These results are not consistent with the positive induced index change of the grating as denoted by its positive $\Delta\lambda_B$ (Fig. 4), which corresponds to the dc component of the grating structure.

The phosphate grating stability was assessed by annealing the device from 20 °C to 400 °C for 1 h at each temperature increment. At constant temperature, the grating spectrum was monitored to evaluate the rate of grating decay. For example, the thermal decay at 300 °C is presented in Fig. 4 showing that

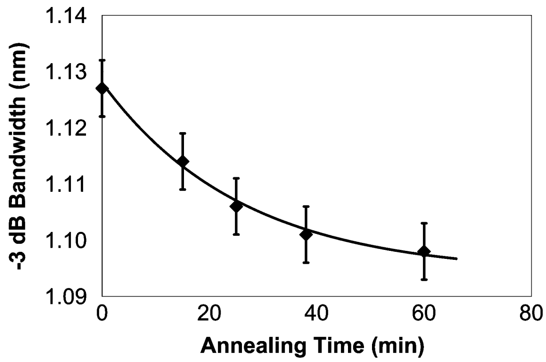

Fig. 4. Isothermal decay of the phosphate refractive index variation at 300 °C follows an exponential decay (solid line). The 5-pm error in the bandwidth measurement is denoted by error bars.

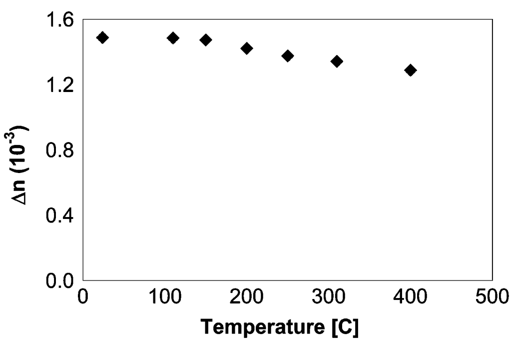

Fig. 5. Annealing behavior of the refractive index modulation in a phosphate glass Bragg grating.

the grating structure stabilizes after a modest decay during the first 40 min. At the end of each isothermal annealing process, the grating was returned to 20 °C and the spectral measurements were repeated.

Although phosphate glasses have low glass transition temperatures ($T_g = 590$ °C for the INO fiber), the variation in Δn for the whole range from 20 °C to 400 °C shows very little decay (see Fig. 5) demonstrating a very good thermal stability of the phosphate glass grating structure. Even for high pump powers in fiber laser applications, it is likely that the reflectivity of laser cavity mirrors made in this fiber would not degrade significantly.

Compared to the reported thermal stability of a Nd^{3+}-doped phosphate glass waveguide written with a femtosecond IR laser [12], the thermal stability of the Δn of the phosphate fiber grating is higher. The difference may be due to the exact composition of the doped phosphate glasses used or the different level of the femtosecond laser intensity.

IV. Conclusion

Bragg gratings have been written in single-mode heavily doped Er–Yb phosphate fiber using ultrafast IR radiation and a phase mask. Refractive index variations $> 1.5 \times 10^{-3}$ have been obtained after short exposures. The grating growth dynamics and the annealing behavior up to 400 °C were also evaluated. The method presented above could allow for the fabrication of lasers with the total length of only a few millimeters in phosphate glass fibers.

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