Highly Reflective Fiber Bragg Gratings Inscribed in Ce/Tm Co-Doped ZBLAN Fibers

Mohammed Saad, Lawrence R. Chen, and Xijia Gu

***Abstract*— We report highly reflective fiber Bragg gratings (FBGs) photoinduced in the core of Ce/Tm co-doped ZBLAN fibers using a 248-nm excimer laser. We compare the characteristics of the FBGs inscribed in ZBLAN fiber to those produced in silica fiber. We also characterize the strain and temperature responses of ZBLAN FBGs and find that the wavelength can be strain- and temperature-tuned at rates that are 45% and 15% higher, respectively, compared to silica FBGs.**

***Index Terms*— Fiber Bragg grating, fiber laser, mid-IR transmission, ZBLAN fiber.**

I. Introduction

RARE-EARTH doped fluoride (ZBLAN) fiber lasers have tremendous potential as compact, high power, and reliable mid-IR light sources which are in high demand for a variety of chemical sensing applications. Many ZBLAN fiber lasers operating in the mid-IR have been demonstrated, as reviewed in [1]. However, most ZBLAN fiber lasers reported to date are not monolithic in design; bulk optics are used frequently for coupling pump light into the fiber while dichroic mirrors are used for wavelength selection. The use of bulk optic components removes many advantages of all-fiber laser configurations, such as compactness, stability, and simple adjustment/alignment. One essential component to realize monolithic ZBLAN fiber lasers is the intracore fiber Bragg grating (FBG). There are very few reports of FBGs inscribed in ZBLAN fiber. Taunay *et al.* reported ultraviolet (UV)-induced permanent FBGs at 1560 nm in Ce-doped ZBLAN with a Ce concentration of 10,000 ppm [2]; a peak reflectivity of about 10% was obtained, corresponding to a refractive index change of 2×10^{-5} after exposure of the fiber to 2.3×10^5 pulses. Bernier *et al.* demonstrated permanent FBGs photoinduced in both Tm-doped and undoped ZBLAN fibers using a 800 nm femtosecond (fs) laser and a phase mask [4]; an index modulation as high as 0.86×10^{-3} was achieved. Nevertheless, using an fs laser to inscribe FBG imposes stringent requirements on optical alignment as the index modulation is induced wherever the laser beam is focused which may easily extend to the cladding. There are also some previous studies on FBGs written in Ce^{3+}-doped silica fibers. Broer *et al.* demonstrated FBGs at 808 nm with a reflectivity of 10% using 292 nm UV irradiation [5] while Dong *et al.* reported FBGs at 1550 nm with a reflectivity of 2.4% inscribed by a single UV excimer laser pulse at 248 nm [6]. A detailed investigation of photosensitivity in Ce^{3+}-doped silica fiber was also performed in [7]. Although Ce^{3+}-doped silica fiber is not transparent in the mid-IR, these studies showed that the refractive index of Ce-doped fiber could be changed by UV irradiation and that the amount of change was proportional to the concentration of Ce. Recently, there has been renewed interest in Ce-doped silica fibers since Ce co-doping was found to improve the resistance to photo-darkening in high-power 980 nm Yb/Ce/Al fiber lasers [8].

In this letter, we report highly reflective FBGs around 1580 nm and 1930 nm inscribed with UV irradiation from a KrF excimer laser at 248 nm in the core of a single-mode Ce/Tm co-doped ZBLAN fiber. The reflectivity, as high as 96%, was obtained from an FBG of 21 mm in length. The strain and temperature responses of the ZBLAN FBGs were also characterized.

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II. Experiment

The Ce/Tm co-doped fiber used in our experiments is fabricated by IR Photonics in Montreal, Canada and has core and cladding diameters of 10 μm and 125 μm, respectively, and a core numerical aperture of 0.14. The core glass is co-doped with 50,000 ppm of Ce and 4,000 ppm of Tm. The glass preparation process was optimized to obtain a core with such high CeF^3 concentration while maintaining its excellent waveguide properties. For example, lead fluoride was added to the core composition to adjust the numerical aperture of the core.

The ZBLAN FBGs were fabricated by focusing a collimated KrF excimer laser (Lumonics, model: PM844) beam though a phase mask onto the horizontally positioned fiber. The coating of the fiber, about 30 mm long, was removed before UV exposure. The typical energy density of the 248 nm pulses at the fiber was 0.05 J/mm^2 per pulse. The pulse repetition rate was set at 30 Hz and a typical exposure time was 8 min to 12 min. The FBGs had uniform refractive profiles; however, apodization, e.g., with a *sinc* function, is possible. All FBGs were annealed at 100 °C for 8 hours to improve their long-term stability (note that due to the relatively low melting temperature of ZBLAN fiber, annealing was performed at lower temperatures compared to silica fiber). The spectrum

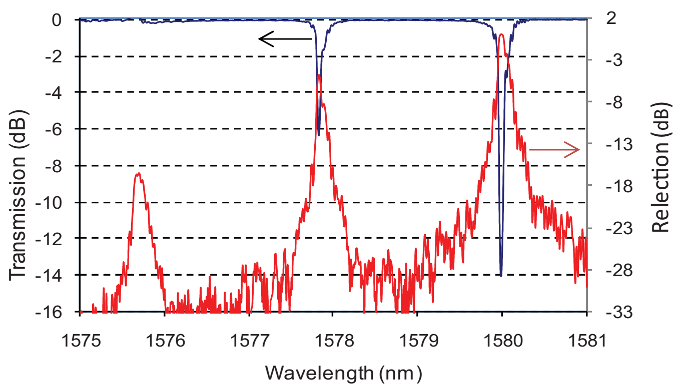

Fig. 1. Transmission and reflection spectra of a 21 mm FBG at 1580 nm in Ce/Tm co-doped ZBLAN fiber showing 3 modes. OSA resolution bandwidth: 15 pm.

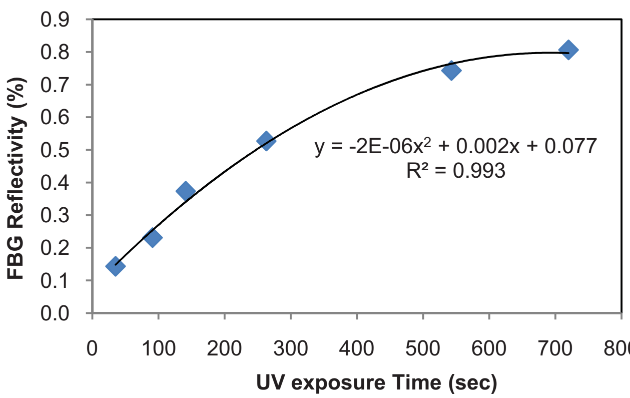

Fig. 2. Evolution of FBG reflectivity as a function of UV laser exposure time.

of the FBG at 1580 nm was monitored during UV exposure with an optical spectrum analyzer (OSA) (Ando, model AQ-6310B) while a second OSA (Yogokawa, model AQ6375) was used to characterize the FBG at 1930 nm.

III. Results and Discussion

First, we used a phase mask with a period of 1060 nm to write FBGs 21 mm in length. After 12 min of irradiation ($\sim$2.16 $\times$ 10^4 pulses), three reflective peaks around 1580 nm were obtained as shown in Fig. 1. Note that since the 10/125 μm ZBLAN fiber is designed for single-mode operation in the mid-IR, the fiber supports several modes at 1580 nm. After annealing, the transmission loss peak of the fundamental mode reached -14.0 dB, corresponding to a reflectivity of 96%; the 3 dB bandwidth is 84 pm.

To understand the growth dynamics of the FBG, we also measured its reflectivity as a function of UV exposure time (see Fig. 2). The reflectivity increased linearly in the first 5 minutes of UV exposure and then started to saturate. The fiber photosensitivity is estimated to be about 50 times less than H_2-loaded telecommunication fiber, such as SMF-28. The FBG spectra shown in Fig. 1 were measured after 8 hours of annealing at 100 °C. The spectra were measured again after three months storage at room temperature and no reduction in reflectivity was observed. Thus, the FBG is relatively stable at room temperature.

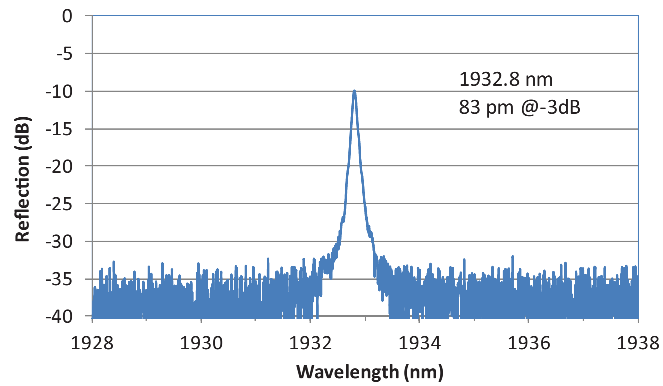

Fig. 3. Reflection spectrum of a 24 mm long FBG at 1930 nm in Ce/Tm codoped ZBLAN fiber. OSA resolution bandwidth: 50 pm.

The ZBLAN FBGs were found to have very different characteristics compared with those inscribed in silica fibers. First, as the FBG reflectivity increased during the fabrication process, there was no measurable shift in central wavelength. This contrasts grating formation dynamics in silica fiber where typically increases in the peak refractive index modulation induced by longer UV irradiation are accompanied by a corresponding increase in average refractive index. The results also contrast those presented in [4] in which negative index changes in ZBLAN fiber induced by the 800 fs laser were observed. Second the FBG can be induced with only a few laser pulses; however, its reflectivity decayed within a few seconds if the laser is turned off. To produce a more stable FBG, much longer UV exposure is required. Finally, FBGs written in ZBLAN fiber exhibited stronger birefringence. Using a polarized light source, we have observed that the peak wavelength can shift by 20 pm and the reflectivity can change by as much as 12% depending on the polarization. The spectra presented in Fig. 1 were obtained using a non-polarized broadband light source. These differences may be attributed to the different photosensitivity mechanisms between ZBLAN and silica fiber. In Ce/Tm co-doped fiber, replacing LaF^3 with CeF^3 has very little effect on the refractive index. On the other hand, it is well know that the doping Ge in silica fiber is largely responsible for its photosensitivity and also for increasing its refractive index.

The UV irradiation on ZBLAN fiber induced a broadband loss of $\sim$0.31 dB during the fabrication process (about 9 minutes). Some of the loss was recovered a few minutes after the laser was stopped. However, it is difficult to quantify precisely the permanent UV-induced loss after annealing since low-loss splicing between ZBLAN fiber and silica fiber remains a challenge.

We also inscribed FBGs at longer wavelengths. Using a phase mask with a period of 1300 nm, we obtained an FBG at 1932.5 nm as shown in Fig. 3. The FBG was 24 mm long and has a narrow 3 dB bandwidth of 83 pm. Judging from the triangular shape of the reflection peak, we believe that the measured reflection response is limited by the resolution of OSA used (50 pm).

In order to explore the possibilities of strain or temperature tuning of ZBLAN fiber lasers, the strain and temperature

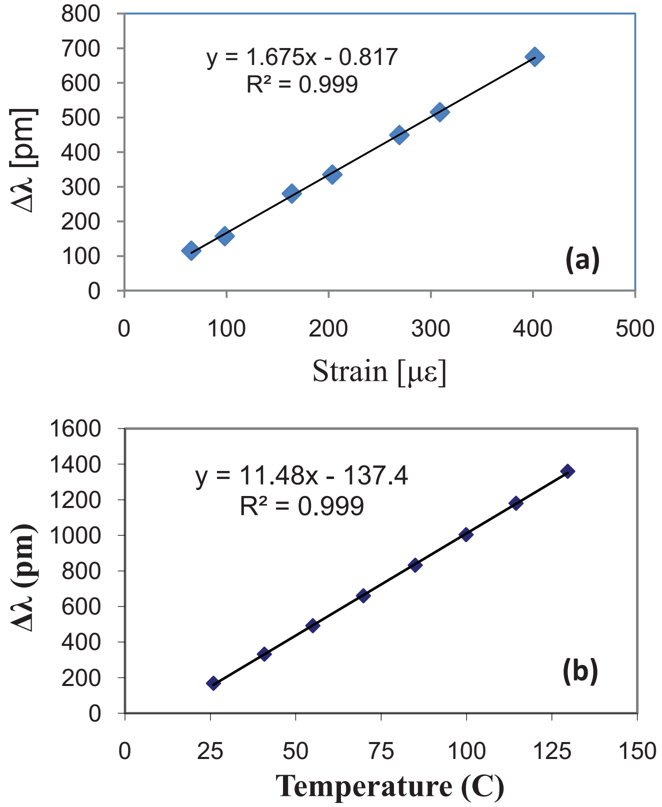

Fig. 4. Strain (a) and (b) temperature dependence of ZBLAN FBGs.

dependence of the FBGs were characterized. The tensile strain was applied to the ZBLAN fiber by adding weight to a hook that was attached to one end of the fiber. The spectral shift of the FBG reflection peak (for the grating at 1580 nm) was recorded as a function of strain as shown in Fig. 4(a). The FBG can be strain-tuned at a rate of 1.67 pm/$\mu\varepsilon$, which is 40% *higher* than what can be achieved in silica fiber. The same FBG was then placed on a temperature-controlled hot plate to characterize its temperature response. As shown in Fig. 4(b), the peak reflection wavelength can be temperature tuned at a rate of 11.5 pm/ °C, which is 15% higher than for silica fiber. The FBGs are slightly more sensitive to temperature which could be attributed to their different coefficients of thermal expansion. However the FBGs are much more sensitive to strain due to the smaller Young's modulus of ZBLAN fiber. These results show that the effective wavelength tuning can be achieved with moderate strain or temperature variation, thereby providing the potential means for developing tunable monolithic ZBLAN fiber lasers.

IV. Conclusion

We have successfully fabricated highly reflective FBGs inscribed in Ce/Tm co-doped ZBLAN fibers using UV (248 nm) irradiation. No hydrogen loading was required to increase the photosensitive response. The FBGs were annealed at 100 °C to enhance their long-term stability. FBGs written in ZBLAN fiber exhibit very different characteristics compared to those produced in silica fiber. We characterized the strain and temperature responses of ZBLAN FBGs and found that the wavelength can be strain-tuned and temperature-tuned at rates that are 45% and 15% higher compared to silica FBGs. We demonstrated FBGs at 1580 nm and 1930 nm; it should be possible to extend the operating wavelengths further into the mid-IR, opening the way for the implementation of monolithic high-power ZBLAN fiber lasers.

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