Bragg gratings written in multimode borosilicate fibers using ultrafast infrared radiation and a phase mask

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ABSTRACT

Inscription of Bragg grating structures is reported in inexpensive multimode borosilicate fibers using femtosecond pulse duration 800 nm infrared radiation and a phase mask. Thermal annealing of the gratings up to 700 °C reveals a behavior similar to Type I-IR gratings made in silica fiber with ultrafast infrared radiation. A portion of the index modulation of the grating is stable up to 500 °C. Below 100 °C, the wavelength shift of the Bragg grating is characterized by ~ 12 pm/°C slope. Above 300 °C, the wavelength shift is ~ 5 pm/°C.

Keywords: fiber Bragg gratings, sensors, borosilicate fibers

1. INTRODUCTION

Borosilicate is an inexpensive glass that has good optical properties in the visible and infrared, transmitting well in the wavelength range from 390 to 1500 nm. It is generally used in optical fiber form to deliver radiation from light sources to detectors. Bundled borosilicate glass fibers are often used in fiber-optic illumination products. Commercially available doped borosilicate glass fibers are multimode waveguides having very large numerical apertures (NA) and refractive indices that vary between 1.46 and 1.68 depending upon the type and amount of dopant used. Borosilicate optical fibers have been used for non-reciprocal rotation (Faraday rotator) applications. One of the most commonly used materials for the 700-1100 nm range are terbium doped borosilicate glasses with a large Verdet constant [1]. Typically the fibers are rich in alkali ions such as Na^-, La^-, or K^- and are suitable for anodic bonding to silicon wafers [2,3]. Borosilicate glasses were also used in all-solid 'holey' optical fibers based on two silicate glasses with a high index-contrast. This microstructured fiber has a cladding in which the holes are filled with low-index glass. High nonlinearity and near-zero dispersion have been reported for these fibers [4]. Fibers with cores made of germanate glass having a refractive index from about 1.6 to about 1.7, codoped with Tm^{3+}, and having borosilicate cladding, could be used as a substitute for the full germanate fibers [5].

Bragg gratings are simple filtering devices that can be inscribed directly in the core and cladding of optical fibers using femtosecond IR lasers [6]. They add functionality to the optical substrates and are currently being used as sensors, optical filters, laser mirrors and for other applications. To date, there has been no report of Bragg grating structures made in borosilicate fiber due to the limitation of the traditional ultraviolet (UV) Bragg grating writing method when applied to borosilicate glass. The high absorption of UV radiation in the borosilicate substrate prevents the light from reaching the core of the borosilicate fiber. We have reported earlier a Bragg grating made with 800nm femtosecond radiation in an ion exchange borosilicate waveguide [7]. Other work of Bragg grating formation was more recently performed in ultrafast IR laser induced waveguides in boro-aluminosilicate substrates [8]. In these cases however, the waveguide cores and thus the laser exposures were made very close to the surfaces of the substrates.

In this manuscript, inscription of Bragg grating structures is reported in central core regions of multimode borosilicate fibers using femtosecond pulse duration 800 nm infrared radiation and a phase mask. Thermal annealing of the gratings up to 700 °C reveals a behavior similar to Type I-IR gratings made in silica fiber with ultrafast infrared radiation. A portion of the index modulation of the grating is stable up to 500 °C. Below 100 °C, the wavelength shift of the Bragg grating is characterized by ~ 12 pm/°C slope. Above 300 °C, the wavelength shift is ~ 5 pm/°C.

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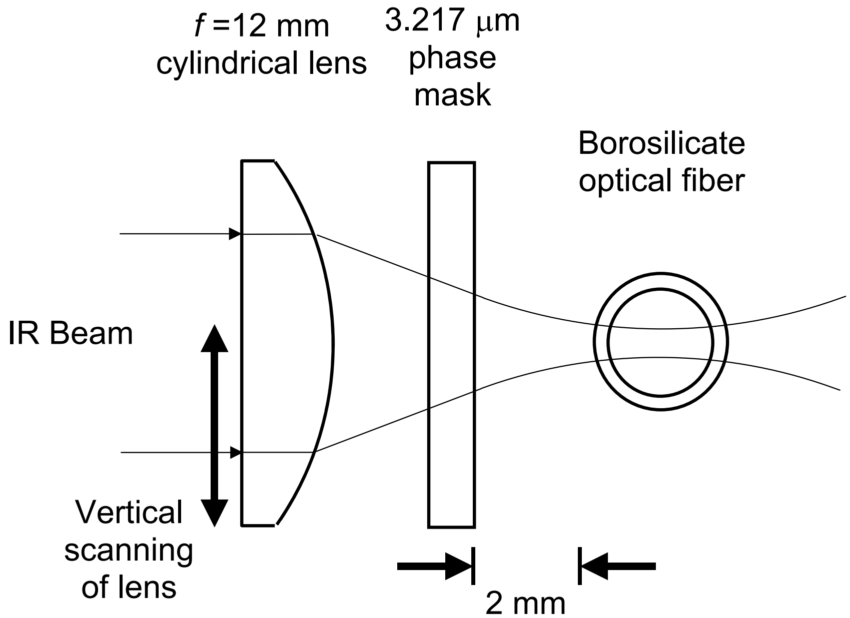

Fig. 1 Schematic representation of the lens-fiber-phase mask geometry for FBG fabrication in the multimode borosilicate optical fibers.

2. EXPERIMENT

Bragg gratings were inscribed in a standard off-the-shelf borosilicate fiber from *Fiberoptic Systems.* The borosilicate fiber has a step-type refractive index structure with a 50 µm outer diameter, a 45 µm core diameter and a numerical aperature (*NA*) of 0.55. The thermo-optic coefficient of the fiber is 2.0 *dn/dT* ($\times 10^{-6}$/°C) with a thermal expansion coefficient of 7 ppm/°C for a temperature range of -30 to 70 °C. The gratings were inscribed using 125 fs autocorrelated pulses of 800 nm IR radiation from a *Spectra-Physics Spitfire* Ti:sapphire regenerative amplifier that was focused through a phase mask onto the optical fiber. The attenuation of the fiber at the 800 nm wavelength of the femtosecond pulses is ~ 0.5 dB/m. The grating was probed at ~ 1250 nm where the attenuation is ~ 0.6 dB/m. The refractive index of the borosilicate material is stated by the manufacturer to be 1.58.

The fiber was placed on a writing jig, 2 mm behind a third order phase mask of 3.217 µm pitch. Femtosecond pulses with a 6.4 mm Gaussian beam diameter were focused with a 12 mm focal length lens through the phase mask into the center of the borosilicate fiber. In order to cover the entire fiber core, the focused beam was translated across the borosilicate fiber by a precision translation stage at a speed of 10 µm/min. The pulse repetition rate of the laser was set to 200 Hz. A schematic of the exposure set up is shown in Fig. 1. The inscription of the grating was monitored using a multimode fiber coupler made of 60 µm diameter multimode silica fiber, a laser diode with an emission spectrum centered at 1250 nm and an *ANDO* optical spectrum analyzer. One of the output ports of the coupler was butt-coupled and index matched to the borosilicate fiber using index matching oil with a refractive index of 1.5. The laser diode signal was sent through one of the input ports and the spectrum analyzer collected the reflected signal from the grating made in borosilicate fiber via the second input port of the coupler (see Fig. 2). The fiber was then placed under the

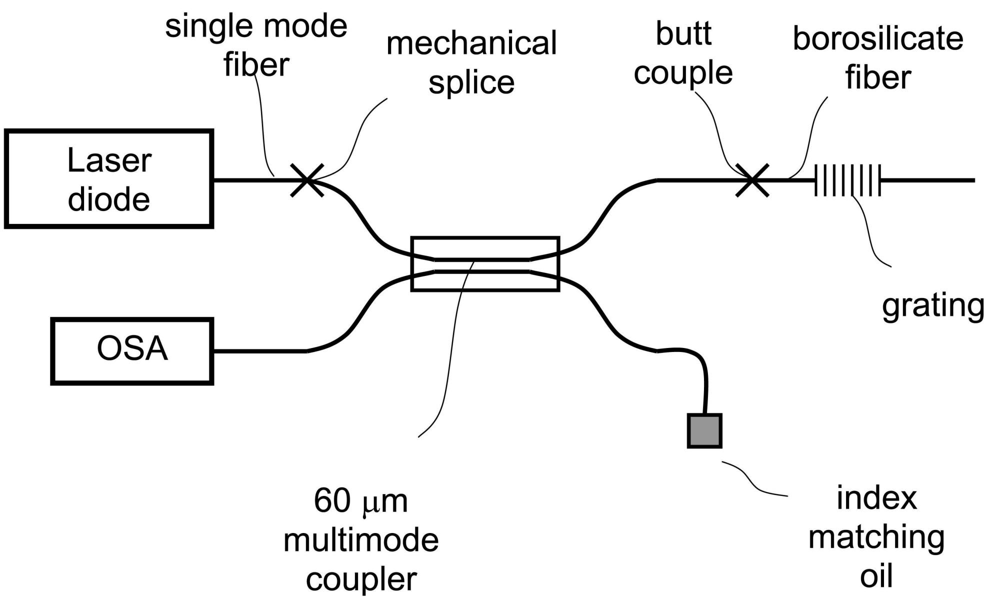

Fig. 2 Diagnostic setup for monitoring spectral response of the borosilicate fiber grating

objective of a high-resolution microscope and the image of the grating structure imprinted in the borosilicate fiber was recorded.

Annealing tests were performed in a micro-oven with a 30 mm long heating chamber and a heating range up to 1500 °C. The borosilicate fiber containing the Bragg grating was placed in a fiber jig with only one clamping point to allow for free expansion of the fiber when heated. The clamped end of the fiber was butt-to-butt aligned to the output port of the coupler using index matching oil in order to improve the coupling. In order to position the Bragg grating within the micro-furnace, a He-Ne laser was connected to the input port of the multimode coupler. The red light scattered by the Bragg grating in the borosilicate fiber was then used to position the grating accurately within the center of the furnace where the temperature distribution was at its maximum. The micro-furnace temperature was monitored at its center using an ultrafast IR laser induced Bragg grating made in standard telecom SMF-28 fiber. Using the He-Ne laser, the Bragg grating in SMF-28 was similarly aligned within the microfurnace to be adjacent to the borosilicate fiber grating. A gradient with a 20% decrease in the temperature from the center to edge of the 20 mm long micro-furnace was observed.

3. RESULTS AND DISCUSSION

The borosilicate fiber was exposed to the laser beam, as described above, starting with lower energy pulses in order to evaluate the damage threshold of the borosilicate material as it interacted with the high intensity femtosecond radiation. After an 8-minute exposure at 200 μJ/pulse, which corresponds to an intensity threshold of 2×10^{13} W/cm^2, very weak fringes were observed in the borosilicate fiber under the microscope. At higher pulse energies, the strength of the grating structure gradually increased until with 800 μJ/pulse, a very strong grating structure could be recorded after only a one-minute exposure. The grating structure observed under the optical microscope is shown in Fig. 3. The reflection spectrum of a grating made with 800 μJ pulses is presented in Fig. 4. The multimode structure of the spectrum measured with a 0.2 nm resolution of the spectrum analyzer, reveals only a few individual modes and a -3 dB bandwidth of ~ 2.5 nm. From the Bragg relation for a third order grating, $\lambda_{Bragg} = 2\, n_{eff}\, \Lambda/3$ where λ_{Bragg} is the Bragg resonance, n_{eff} is the effective index and Λ is the grating pitch, the individual mode corresponding to the longest wavelength seen in the

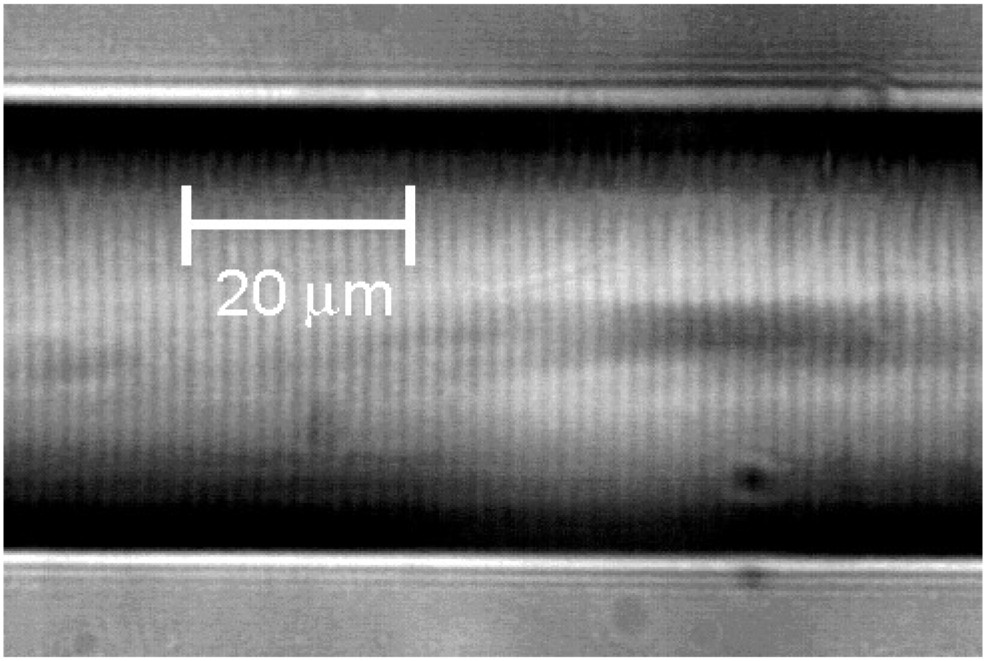

Fig. 3 Microscope image of the Bragg grating in borosilicate glass fiber

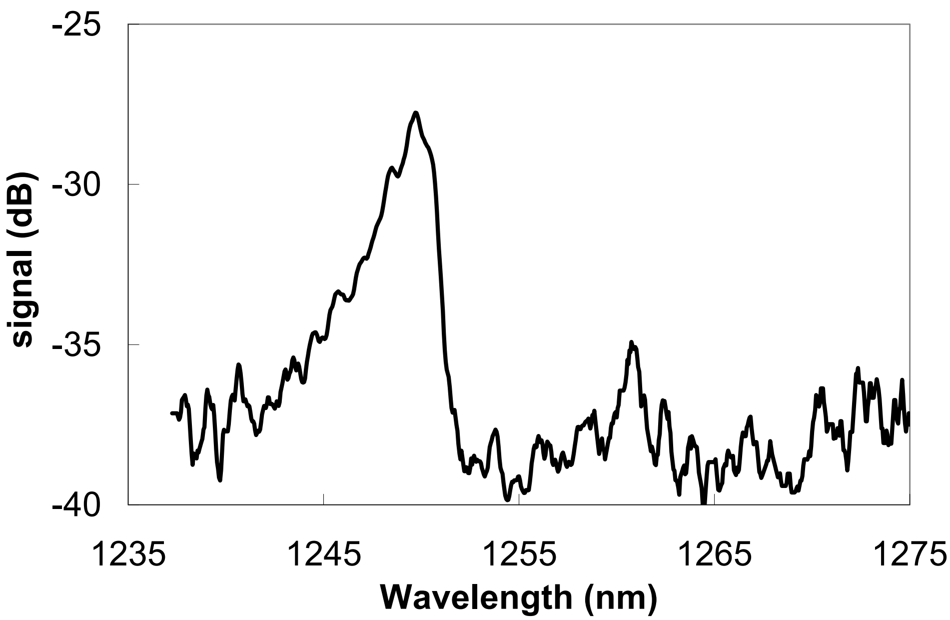

Fig. 4 Reflection spectrum of FBG written in 50 μm diameter borosilicate multimode fiber

spectrum has an n_{eff} of 1.573. It is however difficult to say if this corresponds to the fundamental mode of the 45 μm core fiber structure or if it corresponds to a higher mode as the fundamental mode may be filtered out by the coupler.

In order to evaluate the reflectivity of the gratings, the output port of the coupler was repeatedly cleaved. The highest reflectivity from the cleaved coupler port measured by the spectrum analyzer was considered to correspond to a 4% reflectivity. Using this signal level as a baseline, the spectrum resulting from the grating had a maximum peak

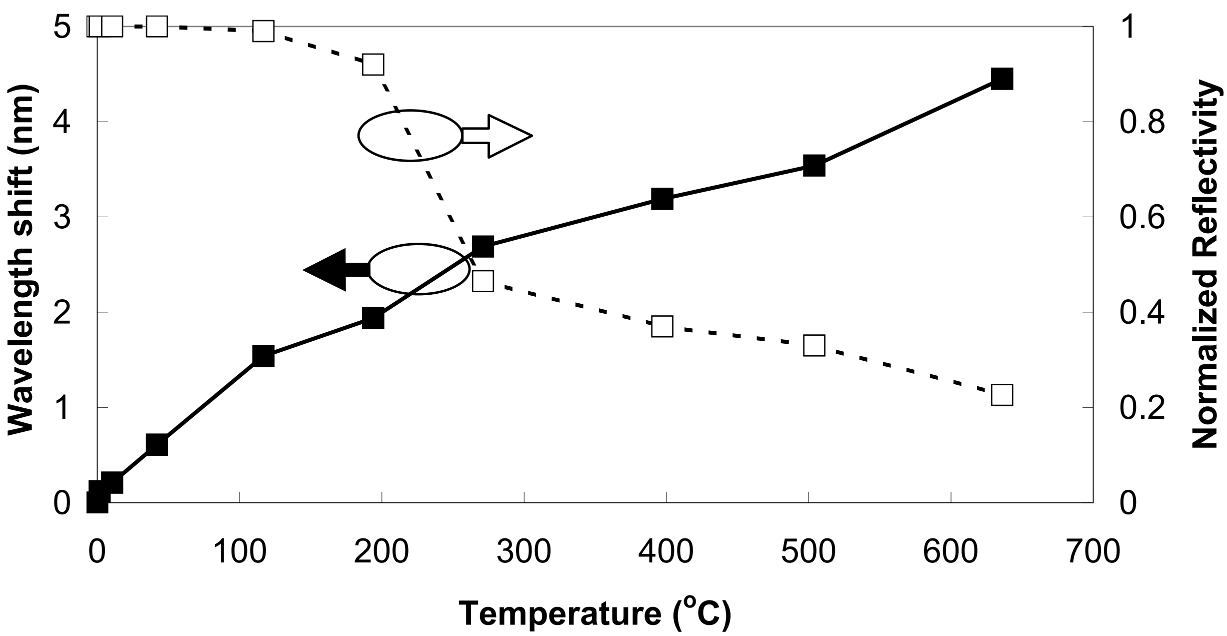

Fig. 5 Wavelength shift (black squares) and normalized reflectivity (white squares) of the Bragg grating in borosilicate fiber against isochronal annealing temperature.

reflectivity just above 4%. It is likely that the probe energy is not being coupled into the fundamental mode of the fiber and therefore the reflectivity of the grating is likely higher.

To study their thermal stability, isochronal annealing experiments were performed on the gratings. The temperature was increased in ~ 100°C increments and allowed to stabilize for 60 minutes. At the end of each annealing period, the wavelength of the peak reflectivity of the multimode spectrum was evaluated and then the heater was deactivated. The micro-oven was allowed to cool and the grating reflectivity was re-measured at room temperature.

The wavelength shift of the Bragg grating spectrum with increasing temperature is denoted by the black squares in Fig 5. According to these measurements, for temperatures below 100 °C, the wavelength shift is characterized by ~ 12 pm/°C slope. At temperature above 300 °C, the wavelength is changing at slower rate of ~ 5 pm/°C. The decay of the refractive index induced by the femtosecond radiation in the borosilicate fiber can be inferred from the decline in the reflectivity of the gratings, which is denoted by the white squares in the Fig 5 when the oven temperature is increased to 700 °C. Although no proper evaluation of the magnitude of refractive index change can be made from the multimode spectrum of the grating, for relatively weak gratings, the change in the refractive index modulation varies linearly with the change in grating reflectivity.

As it can be seen from the normalized reflectivity verses annealing temperature in Fig. 5, the grating structure is very stable up to 200 °C. Above this temperature the grating structure is quickly erased leaving a relatively stable grating residue that survives up to 500 °C. The pattern presented in the Fig 5 is similar to the decay of the refractive index of Type I-IR gratings made in silica fibers [9]. It is important to note however that the reduction in the refractive index modulation of the borosilicate grating occurs at much lower temperatures compared to the type I-IR ultrafast IR laser induced silica Bragg grating. This result is expected owing to the differences in the behavior of the two glasses with temperature. In general, borosilicate glass fiber is capable of operation only up to ~500 °C. Beyond this temperature the fiber slowly starts to soften.

4. CONCLUSIONS

We have demonstrated that it is possible to write Bragg gratings structures in a off-the-shelf 50 μm diameter core borosilicate fiber using infrared fentosecond radiation and the phase mask method. The Bragg grating physical structure and the multimode spectrum were presented. The behavior of the grating structure with temperature up to 700 °C was also reported.

5. REFERENCES

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