Three-dimensional optical sensing network written in fused silica glass with femtosecond laser

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Abstract: A single-step fast-writing method of burst ultrafast laser modification was applied to form a mesh network of multi-wavelength Bragg grating waveguides in bulk fused silica glass. Strain-optic and thermo-optic responses of the laser-written internal sensors are reported for the first time. A dual planar layout provided independent temperature- and strain-compensated characterization of temperature and strain distribution with coarse spatial resolution. The grating responses were thermally stable to 500ºC. To our best knowledge, the grating network represents the first demonstration of 3D distributed optical sensing network in a bulk transparent medium. Such 3D grating networks open new directions for strain and temperature sensing in optical circuits, optofluidic, MEMS or lab-on-a-chip microsystems, actuators, and windows and other large display or civil structures.

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References and links

1. Introduction

The narrow spectral response of fiber Bragg gratings (FBG), long period gratings (LPG), and other type of grating filters provide significant advantages for highly sensitive monitoring of temperature, strain, pressure, acceleration, refractive index, and numerous other physical or chemical phenomena. [1-5] Typically, such optical sensors require physical mounting of a one-dimensional (1-D) grating waveguide devices such as a FBG onto the device under surveillance to measure, for example, temperature or strain [6] or refractive index changes in microfluidic channels [1]. While such grating waveguides can be multiplexed to create multiple sensor points in a flexible 3D layout, distributed 3D optical sensing within bulk transparent media has not been previously demonstrated owing to the difficulty of forming waveguides and gratings arbitrary throughout such bulk media.

Ultrafast lasers have been widely applied for direct fabrication of 3D optical waveguide devices inside various transparent materials [7-13]. Recently, this approach has been extended to form finely segmented waveguides in borosilicate and fused silica glasses that offer strong Bragg grating responses of >35-dB transmission and >90% reflection in a narrow spectral (0.2 nm) resonance. [14, 15] These Bragg grating waveguides (BGWs) are readily formed in a single-step laser exposure with facile tuning of Bragg wavelength, spectral linewidth, and grating strength across the 1200 to 1600 nm telecom band. Further, 3D laser-direct writing facilitates integration through cascading of multiple devices [16] by simple control of laser scan speed and modulation rate. Further, such grating structure can also be embedded into femtosecond laser written waveguides using a point-by-point two scan exposure method. [17]

We demonstrate here, for the first time to our knowledge, a 3-D optical sensor network inside bulk glass that directly measures environmental parameters such as temperature and strain, including their 3-D distribution. The thermo-optic and strain-optic responses of the BGW devices are reported for the first time and found to be similar to traditional FBG responses in silica fiber. Further, thermal annealing reveals a high stability of both optical guiding and Bragg resonance for these devices that is ideal for high temperature sensing environments. The BGW technology promises novel distributed optical sensing applications in 3D that is attractive in small microTotal Analysis Systems through to large civil structures such as buildings and bridges.

2. Fabrication and characterization

Figure 1 illustrates a 3-D optical sensor network which was directly fabricated inside a transparent fused silica glass substrate (Corning 7980) of 50 mm × 50 mm × 1 mm dimension. The waveguides were written with a femtosecond fiber laser (IMRA FCPA μJewel D-400-VR) providing ~300-fs duration pulses at 522-nm wavelength with 500-kHz repetition rate.
The laser beam was modulated by an acousto-optic modulator (AOM; NEOS 23080-3-1.06-LTD) to form laser bursts with 60% duty cycle and 500-Hz modulation frequency. The laser bursts were focused by a 0.55 numeric aperture (NA) aspheric lens to ~1-μm spot size \((1/e^2\) diameter) below the surface of the glass substrate. The glass sample was mounted on two-dimensional (2-D) air bearing motion stages (Aerotech ABL1000 with 2-nm resolution and 50-nm repeatability) and translated transversely to the laser propagation direction with the laser polarization parallel to the translation direction. During the waveguide writing process, the laser bursts formed a series of refractive index voxels that simultaneously provided low-loss waveguiding and high-strength Bragg resonance as first demonstrated in [14] and [15].

For each waveguide in Fig. 1(a), three 16.7-mm long BGW segments with different Bragg resonant wavelengths, \(\lambda_B\), were cascaded in series, by scanning each segment with a different scan speed, \(v\) [16]. The Bragg wavelength was given by:

\[
\lambda_B = 2n_{eff} \Lambda = 2n_{eff} v / f
\]

where \(\Lambda\) is the grating period, \(f = 500\) Hz is the AOM modulation frequency, and \(n_{eff} \approx 1.445\) is the effective index of the BGW as obtained previously [14] for the same exposure parameters. Two identical layers of BGW networks were laser-written at 75-μm beneath the top and above the bottom surfaces of the glass chip. For each layer, two rows and two columns of cascaded BGWs divided the glass chip into 9 sensing zones of 16.7 mm × 16.7 mm in size. The Bragg wavelength of each BGW sensor segment, as labeled in Fig. 1(a), is 1530.0 nm for H1, H4, V1, and V4, 1540.0 nm for H2, H5, V2, and V5, and 1550 nm for H3, H6, V3, and V6. After laser fabrication, the BGW waveguides were butt-coupled with standard SMF28 fibers and bonded with UV curing polymers as shown in Fig. 2(b).

As described in [15], light from a broadband source (Thorlabs ASE-FL7002, 1530 nm to 1610 nm) was passed through a fiber circulator and launched into the BGW segments through the single mode fibers for spectral analysis. Back-reflected light from the sample was routed by the circulator and recorded by an optical spectrum analyzer (OSA, Ando AQ6317B) with 0.01-nm resolution. The reflection spectra were normalized against the power returned by a high reflectivity fiber reflector \((R = 96\%)\). The Bragg resonance wavelength of the various BGW segments were recorded over a 25 to 125 °C temperature range and 0 to ~500 με strain range by heating and bending the glass substrate, respectively.
3. Results and discussion

3.1 Thermal-strain response – theory

By differentiating Eq. (1), the shift in the Bragg grating wavelength, $\Delta \lambda_B$, separates into strain-optic and thermo-optic components given by the induced strain and temperature changes, $\varepsilon_z = \Delta l / l$ and $\Delta T$, respectively, and following [18]:

$$\Delta \lambda_B = 2 \left( \Lambda \frac{\partial n}{\partial l} + n \frac{\partial \Lambda}{\partial l} \right) \Delta l + 2 \left( \Lambda \frac{\partial n}{\partial T} + n \frac{\partial \Lambda}{\partial T} \right) \Delta T \tag{2}$$

The first term in Eq. (2) accounts for changes in the grating spacing and refractive index, $n$, induced by the strain-optic effect, and can be further expressed as [19]:

$$\Delta \lambda_{B-st} = \lambda_B (1 - p_e) \varepsilon_z \tag{3}$$

where the effective strain-optic term is given by $p_e = n^2 [p_{12} - \nu (p_{11} + p_{12})] / 2$, and $p_{11}$, $p_{12}$ are components of the strain-optic tensor and $\nu$ is Poisson’s ratio. For fused silica, Borrelli and Miller applied ultrasonic methods [20] to report $p_{11} = 0.126$, $p_{12} = 0.26$, $\nu = 0.168$, and $p_e = 0.204$. Using these values and $n_{eff} = 1.445$, the expected strain-optic response near 1550 nm is estimated as $\Delta \lambda_B / \varepsilon_z \approx 1.23 \text{ pm/}\mu \text{e}$.

The second term in Eq. (2) follows changes in grating spacing and waveguide refractive index due to thermal expansion and can be simplified to [19]:

$$\Delta \lambda_{B-th} = \lambda_B (\alpha + \zeta) \Delta T \tag{4}$$

where $\alpha = 0.55 \times 10^{-6}/\text{°C}$ is the thermal expansion coefficient for fused silica [17] and $\zeta$ is the thermo-optic coefficient of the waveguide core. For a single-mode fiber, $\zeta$ was measured to be $8.6 \times 10^{-6}/\text{°C}$ [18], leading to an expected temperature sensitivity of $\Delta \lambda_B / \Delta T = 13.7 \text{ pm/°C}$ at 1550-nm wavelength for a fiber Bragg grating. A similar value is anticipated for the bulk BGWs formed in fused silica.

3.2 BGW spectrum

Figure 2 shows a typical reflection spectrum collected from BGW segments H1, H2, and H3, collected from the probe fiber directly bonded to segment H1. The Bragg wavelengths for the three reflection peaks at 1528.2 nm, 1538.4 nm, and 1548.1 nm slightly underestimate (~0.1%) the design values of 1530 nm, 1540 nm, and 1550 nm, respectively. These small shifts arise from experimental variations in laser exposure and indicate an effective index of $n_{eff} = 1.4435$ as opposed to 1.445 obtained previously [14]. The maximum reflectivity of the three peaks decreases from 60.2% (2.2 dB) to 44.7% (3.5 dB) and to 35.3% (4.5 dB) due to higher waveguide propagation loss for BGW segments H2 and H3 which have ~33 mm and ~66 mm extra travel distance from the measurement facet than for segment H1. This attenuation indicates a ~0.3 to 0.4 dB/cm propagation loss which is slightly lower than the 0.6 dB/cm propagation loss reported in [14] for BGWs written with the same exposure conditions. The ~0.3 nm spectral bandwidth (full width half maximum: FWHM) of all three peaks slightly exceeds the ~0.2-nm width reported for the 25-mm long BGWs in [14] due to shorter grating length.
3.3 Temperature sensing

The thermal response of the BGW devices was tested in the 25 to 125°C range by monitoring the Bragg wavelength shifts of the sensor during physical contact with a hotplate. Because the glass sample was thin (1-mm thick by 50-mm wide) and uniformly heated, a one-dimensional heat transfer model [18] could be used to estimate the temperature at each BGW layer ~75 μm from the glass surfaces. Given a 1.3 Wm⁻¹K⁻¹ thermal conductivity for the fused silica and a convective heat transfer coefficient of ~10 W/m²K for air [19], a maximum temperature drop of only 0.07°C at 35°C to 0.71°C at 125°C was expected across the sample thickness (bottom to top surface) and, thus, a uniform substrate temperature could be assumed.

The Bragg wavelength of a BGW with room temperature Bragg wavelength \( \lambda_B = 1550.2 \) nm is plotted in Fig. 3 as a function of hotplate temperature, revealing a linear thermal response (solid line) as expected from Eq. (4). The slope of the line is 10.4 pm/°C, yielding a thermal response that is 24% lower than the 13.7 pm/°C value for the standard SMF28 fiber. Similarly, the thermo-optic coefficient of \( \zeta = 6.16 \times 10^{-6} \) for the fused silica BGW is 28% lower than the optical fiber value (\( \zeta = 8.6 \times 10^{-6} \) [18]), a difference possibly arising from the 3-mol % germanium dopant in the fiber core.

Distributed temperature sensing is demonstrated in Fig. 4 where non-uniform heating of the glass block was provided by heating only the centre of the fused silica sensing chip via a small aluminum block (10 mm × 10 mm × 5 mm) placed between the hotplate and the 3-D sensor chip. The Bragg wavelength shift (with respect to room temperature) of BGW segments...
H1, H2, and H3 are plotted in Fig. 4(a) and segments V4, V5, and V6 are plotted in Fig. 4(b). The wavelength shifts were converted to temperature changes using the 10.4 pm/°C thermal response obtained in Fig. 3 to define the right axis of the graph. It is clear from Fig. 4 that the center sensors, H2 and V2, are hotter than the respective peripheral sensors, H1, H3, V1 and V3, thus confirming a higher temperature in the center of the plate. Such distributed temperature sensing thus permits one to pinpoint the heat source and obtain temperature gradients in bulk glass substrates.

3.5 Strain Sensing

The 3-D BGW network will respond to strain induced by either parallel or perpendicular pressure applied to the BGW. Here, only parallel pressure was studied by bending the sensor plate as shown in Fig. 5(a). Because of the symmetric positioning of the two BGW layers 75 μm from both surfaces, the top and bottom BGW segments will experience equal amounts of tensile and compressive strain, respectively, that shift the Bragg wavelengths by identical magnitudes but in opposite spectral directions. Further, since each Bragg grating has identical temperature response, this strain-gauge arrangement is insensitive to environmental temperature fluctuation – an important advantage for field deployment.

In Fig. 5(a), the central rod was pushed with a micrometer against the glass plate to bend the plate between the two fixed cylindrical rods with displacements up to \( D = 300 \) μm. The strain of the glass plate at the top and bottom waveguide can be expressed as \( \varepsilon = \Delta L / L = h / R \), where \( L = 50 \) mm is the top rod-to-rod arc length subtending twice the half angle, \( 2\theta = L / R \), \( R \) is the sample bend radius under displacement \( D \), and \( h = 425 \) μm is the waveguide to the glass center plane distance. Using the small angle approximation, one obtains a simple relationship between the glass displacement and bend radius:

\[
D = R - R \cos \theta = 2R \sin^2 \left( \theta / 2 \right) = R\theta^2 / 2 = L^2 / 8R, \tag{5}
\]

which then gives the following relationship for strain at the BGW:

\[
\varepsilon = \frac{h}{R} = \frac{8 Dh}{L^2}. \tag{6}
\]
Figure 5(b) plots the measured Bragg wavelength shift with respect to the center beam offset, \( D \), for BGW segments V4, V5, V6, V4B, V5B, and V6B, where B indicates BGWs in the bottom plane. The Bragg wavelength on the top and bottom BGWs shift to longer and shorter wavelength, respectively, as expected by the respective tensile and compressive strains induced for bending as in Fig. 5(a). It is also clear in Fig. 5(b) that much smaller Bragg shifts were induced in the peripheral BGW segments (V4, V6, V4B, V6B). These smaller shifts were accompanied by broader wavelength-chirped lineshapes that overall reflect a range of smaller bending radii and incomplete bending at the end points of the beam. In this way, 3-D distributed optical strain sensing has been demonstrated for the first time in bulk transparent media.

The center BGW segments, V5 and V5B, underwent more uniform bending stress, providing good linear response of wavelength shift with beam displacement as seen in Fig. 5(b). From the slopes of this data, we find a BGW strain-optic sensitivity \( s = \Delta \lambda / \Delta D \) of 2.32 pm/\( \mu \)m and -2.13 pm/\( \mu \)m for the top and bottom BGW pairs, respectively. Combining \( s \) with Eq. (6) yields the Bragg wavelength-strain coefficient, \( \Delta \lambda / \Delta \varepsilon = s \lambda \) \( L \) \( / 8h \), from which we inferred values of 1.38 pm/\( \mu \)e and -1.27 pm/\( \mu \)e, respectively, showing good agreement with the calculated value of \( \Delta \lambda / \Delta \varepsilon = 1.23 \) pm/\( \mu \)e. The sensitivities of the top and bottom BGWs were 20\% and 10\% greater, respectively, than the 1.15 pm/\( \mu \)e reported for standard fused silica FBGs for 1550-nm radiation [19].

The symmetric placement of BGWs in the present 3-D sensor network provides a unique and highly desirable sensing capability that can locally sample the beam bending radius and bending moments from differential strain measurement as in Fig. 5 and provide distributed 2-D and 3-D optical strain sensing. At the same time, this symmetric pairing of BGWs greatly improves the sensor precision by separating out the temperature and other environmental drifting factors which shift the BGW pairs identically in the same spectral direction.

### 3.6 Sensor thermal stability

Because the 3-D sensor chip is directly fabricated in a high temperature glass (pure fused silica), the BGWs are expected to be extremely stable. To assess the thermal stability, 25-mm long BGWs were fabricated in a similar fused silica sample with the same exposure conditions as the 3-D sensor chip. The BGW devices were annealed in a tube furnace in several cycles of increasing temperature and optically characterized after cooling to room temperature for changes in mode profile, Bragg wavelength, and grating strength. The top row of Fig. 6 shows microscope images of the BGWs after various heat tests with the temperature and exposure duration indicated below the figure. There are no visual changes in BGW morphology after all the heating cycles tested up to the maximum temperature of...
1000°C which exceeded the 893°C strain point [21]. The bottom row images in Fig. 6 show a slight increase of the mode diameter (average of the two transverse mode diameters) from ~12 μm to ~14 μm after 8 hours of heating at 250°C. The mode diameter increased slightly to ~15 μm after subsequent baking at 500°C for 1 hour, but expanded significantly to ~17 μm after a further 1 hour anneal at 750°C. This weakening light confinement indicates a reduced average waveguide refractive index. After annealing for 1 hour at 1000°C, the laser exposed track was still visible but no mode profile could be detected. Since the laser modification volume consists of complex structures with both positive and negative refractive index change [22], this data suggests that the positive index structures are less thermally stable than the other morphological structures that survived the high temperature annealing.

![Fig. 6. Microscope images (top) and mode profiles (bottom) of BGWs written in fused silica glass by burst writing at 60% AOM duty cycle, following various heating cycles.](image)

Table 1 summarizes the BGW grating strength and propagation loss tested after the heating cycles described in Fig. 6. The BGW grating strength remained stable (~35 dB) for annealing cycles up to 250°C and decayed only slightly by ~3 dB at 500°C. After the heating at 750°C, the grating transmission decreased dramatically to only ~3 dB, representing a larger reduction in the AC refractive index modulation contrast. Similarly, the waveguide propagation loss remained stable at ~0.6 dB/cm after baking cycles at 250°C and 500°C, but increased to 2.2 dB/cm after annealing at 750°C. This increased loss may arise from microstructural changes thermally induced in the waveguide. Also, the larger mode may overlap more strongly with low index or laser-damage structures formed just outside the waveguide core region (see Fig. 7 and 10 in [22]). Further, the Bragg wavelength shifted by ~0.25 nm after the 750°C annealing step which suggests a $2.3 \times 10^{-4}$ reduction of the effective refractive index change that only represents ~2% of the total induced refractive index change of ~0.01 as reported in [14]. These results point to a much higher temperature resistance for the fused silica BGWs compared with the BGWs written inside borosilicate glass, where grating strength degraded considerably at 500°C and propagating modes became undetectable at 750°C [15]. This trend follows the high and low glass strain point of 893°C for fused silica and 666°C for borosilicate, respectively. As a result, fused silica BGWs are preferable for high-temperature applications.
Table 1. Grating strength and propagation losses of the burst written fused silica BGW under various heat cycles.

<table>
<thead>
<tr>
<th>Anneal cycles</th>
<th>Grating strength (dB)</th>
<th>Propagation loss (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hours</td>
<td>34.8</td>
<td>0.6</td>
</tr>
<tr>
<td>8 hours at 250 ºC</td>
<td>34.8</td>
<td>0.6</td>
</tr>
<tr>
<td>1 hour at 500 ºC</td>
<td>31.8</td>
<td>0.6</td>
</tr>
<tr>
<td>1 hour at 750 ºC</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>1 hour at 1000 ºC</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

4. Conclusion

A novel 3-D distributed BGW sensing network was fabricated inside fused silica glass by direct ultrafast-laser writing and found to be a viable temperature and strain sensor with high sensitivity. 3-D distributed thermal and strain sensing was demonstrated by pinpointing a local heat source and measuring non-uniform strain in bulk glass. The sensor chip was also survived exposure to very high temperature up to 500 ºC, which opens sensing to a broad range of high temperature applications. The 16.7 mm spatial resolution can be further improved by introducing shorter BGW segments, which could lead to high resolution strain and temperature sensing in rigid structures such as building or bridges through to biochips and microreactors. Further, each BGW device (24 in present sample) can be written to have different Bragg wavelengths and be conveniently monitored with a single low-cost broadband source. To our best knowledge, this is the first demonstration of a 3-D distributed sensor network fabricated directly inside a transparent material. Extension of this technology for sensing of other environmental quantities is expected.

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