Temperature-compensated fiber-optic 3D shape sensor based on femtosecond laser direct-written Bragg grating waveguides

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Abstract: Temperature-compensated 3D fiber shape sensing is demonstrated with femtosecond laser direct-written optical and Bragg grating waveguides that were distributed axially and radially inside a single coreless optical fiber. Efficient light coupling between the laser-written optical circuit elements and a standard single-mode fiber (SMF) was obtained for the first time by 3D laser writing of a 1 × 3 directional coupler to meet with the core waveguide in the fusion-spliced SMF. Simultaneous interrogation of nine Bragg gratings, distributed along three laterally offset waveguides, is presented through a single waveguide port at 1 kHz sampling rate to follow the Bragg wavelength shifts in real-time and thereby infer shape and temperature profile unambiguously along the fiber length. This distributed 3D strain and thermal sensor is freestanding, flexible, compact, lightweight and opens new directions for creating fiber cladding photonic devices for a wide range of applications from shape and thermal sensing to guidance of biomedical catheters and tools in minimally invasive surgery.

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1. Introduction

Fiber Bragg gratings (FBGs), first discovered by Hill et al. [1], are invaluable optical devices in optical communication, sensing, and fiber laser applications. During the past decade, there has been a growing interest in developing bend sensors in a single optical fiber, which can measure both the magnitude and direction of strain (so-called directional or vector sensing). Conventional FBGs are naturally insensitive to bend-induced strain due to the grating-sensor placement in the neutral stress axis of the optical fiber. Hence, several sensor schemes have been developed using long-period gratings [2, 3], tilted FBG [4, 5], and FBG-embedded multimode optical fiber [6] that break from the limitation of cylindrical symmetry and enable vector sensing in optical fibers. However, these methods rely on sensing amplitude or wavelength shifts amongst many weak cladding or multimode resonances to infer the bend magnitude and direction, limiting the number of sensing elements that can be cascaded along a single waveguide for multi-point sensing over long fiber length. A more promising direction is to directly detect the strong FBG resonances when formed into a multicore optical fiber (MCF), where eccentric waveguide positions facilitate not only temperature-insensitive vector sensing [7, 8, 9] but also shape and position sensing over long fiber lengths [10, 11]. However, simultaneous interrogation of the multiple waveguide cores remains a major packaging challenge in this approach, demanding high precision and cumbersome alignment with, for example, fan-out optical fibers or integrated photonic lantern [12].

Bragg gratings are conventionally photo-inscribed into the pre-existing core of photosensitive optical fiber by holographic or phase mask interference of UV laser light [13]. Alternatively, femtosecond laser direct writing in transparent materials exploits nonlinear light-material interaction, which can induce highly localized and positive refractive index modification without the need for photosensitive response. Hence, Bragg gratings have also been inscribed with femtosecond lasers in standard single-mode optical fibers (SMFs) with point-by-point [14, 15], line-by-line [16] and burst mode writing [17]. Grenier et al. extended the writing of Bragg grating waveguides (BGWs) from the fiber core to the cladding of SMF and no-core (or coreless) optical fibers [17], effectively creating a FBG-embedded MCF bend sensor. Similarly, extending laser writing of 3D directional couplers from bulk glass [18, 19] to inside optical fibers offers the novel opportunity to couple light between the radially and axially distributed BGW sensor elements and meet with a center waveguide core that overcomes the major packaging challenge with such MCF-type sensors.

In this paper, a fiber-optic 3D shape, position and temperature sensor is introduced, consisting of a radially and axially distributed network of BGWs in a coreless optical fiber. Optical components, which were laser written inside the coreless fiber, included a 1 × 3 directional coupler to distribute light into the center and off-center fiber positions for unambiguous temperature and strain measurement, respectively. The sensor was fusion spliced onto a SMF to offer simultaneous monitoring of nine BGWs through a single waveguide port, overcoming the packaging challenge of the MCF approach. Both static and dynamic shape monitoring to a 40 mm bend radius together with temperature sensing in the 24 to 100 °C range is reported at a 1 kHz sampling frequency. This distributed 3D strain and thermal sensor is freestanding, flexible, compact and lightweight. Such a device is attractive in wide ranging applications from shape and thermal sensing to guidance of biomedical catheters and tools used in minimally invasive surgery.

2. Fabrication and experimental setup

Figure 1(a) shows a diagram of coreless fiber sensor fusion spliced to SMF-28 optical fiber, while undergoing femtosecond laser writing of waveguides, BGWs and directional couplers. The optical components include three parallel waveguides, one 1 × 3 directional coupler, two...
waveguides with S-bends, and nine BGWs that were all written in a single exposure step with a femtosecond laser (230 fs, 522 nm, 1 MHz) following the procedure previously presented by Grenier et al. [17]. The laser was focused into the fiber with a 100×, 1.25 NA oil-immersion lens to avoid the strong astigmatic and spherical aberration of the cylindrical fiber geometry. A laser exposure of 71 nJ pulse energy and 0.1 mm/s scan speed yielded optimal low loss waveguides of 0.5 ± 0.1 dB/cm as determined by the cutback method. The tighter focusing produced slightly asymmetric mode field diameters of 7.5 µm × 6.5 µm that are 32% smaller than for waveguides written without an oil-immersion lens [20]. The BGWs were structured in tandem with the uniform waveguides, with the desired Bragg wavelengths, $\lambda_i$, controlled by the frequency applied to an acousto-optic modulator as described in [21] for exposure at 60% duty cycle.

![Fig. 1. Schematic (a) of a 3D distributed shape and thermal sensor written in coreless fused silica fiber by a femtosecond laser focused with an oil-immersion lens. Microscope images of the fiber cross section (125 µm diameter) at the coupling (b) and sensor (c) regions, showing the arrangement of the internal laser-written waveguides.](image)

The coreless fiber made of fused silica was drawn to the same diameter (124.7 ± 0.7 µm) as that of the SMF-28 optical fiber. In Fig. 1(a), a single waveguide was written within ±2 µm of the center of the coreless fiber to couple efficiently with the SMF. Two additional waveguides are also shown written slightly offset and in parallel with the center waveguide to define a 1 × 3 directional coupler. Approximately equal power splitting around 1310 nm wavelength was found with a coupling length of 500 µm and 9 µm lateral offsets in the right-angled isosceles triangle arrangement shown in Fig. 1(b). The two off-center waveguides were designed to follow S-bend trajectories of two constant radius (40 mm) arcs to reach the 40 µm radial positions as shown in the cross-sectional image Fig. 1(c). In the distributed sensing region, three 1 cm long BGWs were written along each waveguide at 2 cm center-to-center separations, forming three groups of axially co-located BGW triplets as illustrated in Fig. 1(a). Each BGW was defined by a different Bragg resonance from $\lambda_1 = 1280$ nm to $\lambda_9 = 1320$ nm, with 5 nm increments. This short to long wavelength ordering ensured that the spectrum of cladding-mode-coupled light from an upstream BGW would not coincide with the resonance of a downstream BGW [14].

The nine BGWs were simultaneously interrogated by launching broadband light with a 1275 to 1345 nm spectrum and field polarization ellipticity of 1.4 through an optical circulator into
the SMF shown in Fig. 1(a) with back reflections recorded with either an optical spectrum analyzer (OSA; Ando AQ6317B) or a spectrometer (Ibsen I-MON 512E). The OSA provided high spectral resolution of 15 pm at slow sampling rates of less than 2 Hz, while the spectrometer provided high sampling rates of 1 kHz at a lower spectral resolution of 140 pm. Therefore, the OSA was preferred in resolving the polarization splitting arising from birefringence expected in the laser-written waveguides [22], whereas the spectrometer was most attractive for rapid dynamic sensing with resolution sufficient for both thermal and strain calibration.

3. Sensor calibration

Following an iterative optimization procedure for balancing the splitting ratio in the $1 \times 3$ directional coupler, all nine BGW resonances in the coreless fiber could be observed in reflection on probing through the SMF. Representative reflection spectra are shown in Fig. 2, comparing the OSA and the spectrometer recordings with the fiber aligned straight and unstrained at room temperature of 24 °C. All Bragg wavelengths were blue shifted by $\sim 1$ nm on release of the fiber strain following the laser exposure. An assessment of the reflectance of the first interrogated BGW triplets, $\lambda_1, \lambda_4, \lambda_7$, with the higher resolution OSA spectrum (bottom in Fig. 2) yielded relative power splitting ratios of 24.5%, 21.7%, and 53.8% for round-trip coupling to the center and side arm waveguides, respectively. These values are consistent with the single-pass coupling ratio of 31.1%, 26.7%, and 42.2% obtained from the power measured out of each waveguide arm relative to the sum of their powers. This nearly balanced power splitting was required to ensure that the Bragg resonances of the furthest BGWs ($\lambda_3, \lambda_6, \lambda_9$) could be detected and tracked above the detection noise floor. The splitting was nearly polarization independent owing to a low waveguide birefringence over such short coupling length (500 µm).

Also seen in the OSA spectrum is a logarithmic falloff of $\sim 5$ dB between the downstream BGWs, $\lambda_3, \lambda_6, \lambda_9$, with respect to their corresponding upstream BGWs, $\lambda_1, \lambda_4, \lambda_7$, inferring a BGW propagation loss of 0.7 dB/cm that exceeded the 0.5 dB/cm loss measured by cutback for a uniform waveguide. The partial waveguide segmentation in the BGW is expected to contribute a higher radiation loss. A total insertion loss of 5.1 dB measured for the present device therefore divides into waveguide propagation loss of 3.35 dB and a 1.75 dB loss from the combined mode and alignment mismatch at the fusion splice and scattering from the $1 \times 3$ coupler.
The expanded OSA spectrum inset in Fig. 2 reveals wavelength splitting of $\Delta \lambda_b = 175 \pm 2$ pm due to BGW birefringence for Bragg wavelength $\lambda_2$, resolving into two peaks each with $72 \pm 2$ pm full width at half maximum (FWHM) that was not instrument limited in resolution. This wavelength splitting was typical for all the BGWs, indicating a birefringence value of $(1.97 \pm 0.03) \times 10^{-4}$. This birefringence is twice the value reported previously for BGWs written in bulk glass with 0.5 MHz laser repetition rate [23], owing to a stronger material modification that was associated with ~2.5 times higher net laser exposure used in this work.

The reflection spectrum of the unstrained sensor as recorded with the lower resolution spectrometer is also shown in Fig. 2 (top). Only a single reflection peak of $330 \pm 30$ pm (FWHM) linewidth was observed at each Bragg wavelength, which is ~5-fold wider than with the OSA recording owing to a low spectrometer resolution of 140 pm. Despite this lower resolution, the 1 kHz sampling rate of the spectrometer offered rapid real-time monitoring of the Bragg recording owing to a low spectrometer resolution of 140 pm. Despite this lower resolution, the recorded reflection spectrum was up-sampled by 50-fold with cubic spline interpolation (VTK, Kitware Inc.) and followed with a peak finding algorithm (written in C++) on each Bragg recorded reflection spectrum to resolve major Bragg responses. To improve the precision in charting the center Bragg resonance wavelength, each recorded reflection spectrum was up-sampled by 50-fold with cubic spline interpolation (VTK, Kitware Inc.) and followed with a peak finding algorithm (written in C++) on each Bragg resonance with a ~5 pm precision in static sensing.

For strain and temperature calibration, the present shape sensor was found to follow the conventional response of FBGs in SMFs, which relates the Bragg wavelength shift, $\Delta \lambda$, to strain, $\varepsilon$, and temperature variation, $\Delta T$, as expressed by Eq. (1) [24].

$$\frac{\Delta \lambda}{\lambda} = (1 - p_e)\varepsilon + (\alpha + \frac{1}{n} \zeta) \Delta T.$$  

Here, $p_e$ is the effective strain-optic constant, $\alpha = 0.55 \times 10^{-6}$ K$^{-1}$ is the thermal expansion coefficient for fused silica [25], $n = 1.447$ is the refractive index for fused silica near 1300 nm wavelength [26], and $\zeta$ is the thermo-optic coefficient.

For temperature calibration, the unstrained sensor was placed in an oven (Despatch LAC1-10-5) and heated over the range of 24 to 250 °C, yielding the plot of Bragg wavelength $\lambda_1$ versus temperature shown in Fig. 3(a). The linear fit of the data follows a thermal response of $\Delta \lambda / \Delta T = 9.1 \pm 0.6$ pm/K, which is slightly lower than the 10 pm/K FBG thermal response commonly reported at 1550 nm wavelength [24]. This lower thermal response is expected for fused silica due to a higher refractive index and lower thermo-optic coefficient at 1300 nm than at 1550 nm [26]. The experimental data provided a thermo-optic coefficient of $\zeta = 9.5 \times 10^{-6}$ K$^{-1}$ at 1300 nm which is similar with the value of 8.54 $\times 10^{-6}$ K$^{-1}$ interpolated from [26].

Strain calibration of the fiber sensor was carried out at room temperature by first rotating the fiber to azimuthally align a side arm waveguide for maximum strain sensitivity, followed by the bending of the fiber into circles of different radii, $\rho$, between 40 and 117 mm. The bend-induced strain, $\varepsilon = d / \rho$, was calculated using the expected radial offset position of $d = 40$ µm as designed for the side arm waveguides and observed in the fiber’s cross-sectional image in Fig. 1(c). The expected linear relationship between Bragg wavelength $\lambda_7$ and strain, as seen in Fig. 3(b), yielded a strain sensitivity of $\Delta \lambda / \varepsilon = -1.06 \pm 0.06$ pm/µε, which agrees well with the typical FBG strain response of 1 nm/millistrain at 1300 nm [24]. The observed strain response offered a strain-optic constant of $p_e = 0.194$ that matches closely within 5% of the 0.204 value reported for fused silica [27]. Hence, the measured thermo-optic and strain-optic coefficients do not appear to be affected by the laser modification of glass structure.

The intended orthogonal arrangement of side arm waveguides in the distributed sensing volume of the fiber proved simple and straightforward to uniquely determine the sensor’s azimuthal angle, $\phi$, and the bending radius from the fractional Bragg wavelength shifts, $\Delta \lambda / \lambda$, of the two off-center waveguides in each BGW triplet. Repeated measurements of the Bragg resonant wavelengths were recorded for the fiber wrapped around a 126 mm diameter cylinder in ran-
Fig. 3. Wavelength shift of Bragg resonance $\lambda_1$ with temperature (a) during heating of the straight fiber, and wavelength shift of Bragg resonance $\lambda_7$ with strain (b) during fiber bending at room temperature.

domin azimuthal orientations at room temperature. A plot of the fractional Bragg wavelength shift against the azimuthal angle is shown in Fig. 4 for the first interrogated BGW triplet, where the angle was calculated trigonometrically from the ratio of wavelength shifts of the side arm BGWs. Each of the three BGW data follows an expected sinusoidal dependence (solid lines in Fig. 4), where the observed maximum shifts in the Bragg wavelength of $\Delta \lambda/\lambda = 5.12 \times 10^{-4}$, $4.96 \times 10^{-4}$, and $0.36 \times 10^{-4}$ provided a more precise determination of the radial offsets at $d = 40.0, 38.8, \text{and } 2.8 \ \mu m$ for side arm 1, side arm 2 and center BGW positions, respectively, from the fiber’s neutral axis. These slight radial misalignments resulted in a reduced angular separation of $85.9^\circ$ subtended by the side arms with respect to the fiber center as determined from the angular displacement of the sinusoidal BGW data for the two side arms in Fig. 4. These radial and angular offsets were then used to improve the precision of the temperature and strain measurements of the fiber sensor, and thus avoided measurement errors as high as $7^\circ C$ for temperature, 3% for bending radii, and $2^\circ$ for azimuthal angle.

Fig. 4. Fractional wavelength shifts recorded from BGW triplets $\lambda_1$, $\lambda_4$, $\lambda_7$ at various azimuthal positioning of the fiber bent to 63 mm radius of curvature at room temperature.
The wavelength shift data in Fig. 4 follow their respective sinusoidal representations with a standard deviation of $\Delta \lambda / \lambda = 3.5 \times 10^{-5}$. Applying this variation in Eq. (1) reveals a measurement uncertainty of $\pm 5 ^\circ$C in temperature, $\pm 1.1 \times 10^{-3}$ mm$^{-1}$ in curvature, and a minimum $\pm 2.5^\circ$ in azimuthal angle for the case of 40 mm bend radius. This imprecision originates primarily from random rotation of the light source polarization axes (1.4 field ellipticity) in the fiber under varying bending and temperature conditions that reduces the peak-finding algorithm to preferentially lock onto either one of the TE or TM Bragg resonance peaks (Fig. 2 inset). An asymmetric line shape therefore forms across the two polarization peaks on 175 pm separation, which convolves with the spectrometer resolution of 140 pm to select either of two wavelength readings separated by 112 pm. This suggests a standard deviation of $\Delta \lambda / \lambda = 4.3 \times 10^{-5}$ that matches the variance of data points seen in Fig. 4. This imprecision could be improved $\sim 10$-fold ($\Delta \lambda = \pm 5$ pm) by any means of probing a single polarization eigenmode of the BGWs. Other methods such as post thermal annealing [28] or femtosecond laser-written stress bars [20] could also be applied to reduce the birefringence of the laser-written waveguides and improve the wavelength precision.

4. Fiber shape sensing

Fiber shape sensing is first presented in the absence of thermal gradients as illustrated in Fig. 5(a) by the four examples of non-uniform fiber bending at room temperature. Red diode laser light was launched into the fiber in order to record the scattered light optical images shown superimposed in Fig. 5(a) for four different sensor shapes. All nine Bragg wavelength shifts were corrected from their respective off-center waveguide positions and applied in Eq. (1) to infer the bending radius and azimuthal bending plane at each axial position of BGW triplets. These values were decomposed into bend radii on orthogonal planes, and then applied in cubic spline interpolation to calculate a continuously varying curvature and azimuth everywhere along the length of the fiber. To accommodate the large geometric deformation, the shape and position of the fiber was then determined by the finite element method of co-rotational analysis, which discretized the fiber into curved rigid beam elements that were aligned tangentially at each node [29].

Fiber shapes were calculated for each of the fibers imaged in Fig. 5(a), and plotted in Fig. 5(b) as dashed lines overlaid onto the same fiber images. The images reveal a small positional error of $\sim 0.6$ mm in the proximity of the BGW triplets (highlighted in green), with the error increasing dramatically when far outside the distributed BGW sensing zone as seen for the case of large curvature bending of $1.9 \times 10^{-2}$ mm$^{-1}$ in the topmost fiber shape in Fig. 5(b). Overall, the fiber shape sensing could be precisely followed for lateral BGW displacements of up to 26 mm and bending radii as small as 77 mm.

An example of real-time 3D shape sensing with the present fiber sensor is presented in Fig. 6 (Media 1). Three orthogonal views (i.e. one end view and two side views) of the fiber shape were calculated in real-time from the nine Bragg wavelength shifts and displayed on the computer monitor while a video recording of the physical fiber is shown in the foreground as the fiber was subjected to various degrees of bending at room temperature. The locations of the BGW triplets are marked in blue on the physical fiber. Media 1 is divided into three segments, titled ‘Simple Deflections’, ‘Spins’ and ‘Large Deformations’, in all of which the calculated fiber shapes mirrored closely to that of the physical sensor device. In the first segment, lateral deflections of the fiber tip are precisely followed in the calculated end view (leftmost display panel) in four orthogonal azimuthal directions. In the Spins segment, counterclockwise and clockwise fiber rotation is followed smoothly and continuously over all 360° azimuthal angles in the leftmost display panel. In the last segment, the co-rotational analysis is also seen to closely follow more complex fiber shapes such as a hook, calculated in the side view shown in...
Fig. 5. Superimposed photographs (a) of the fiber sensor bent in various shapes showing scattered light while end-fired with a red diode laser. Calculated fiber profiles (b) in dashed lines superimposed onto the fiber shapes. Green lines indicate the BGW triplet locations.

Fig. 6. A single-frame excerpt from the video recording (Media 1) showing a side image of the 3D fiber shape sensor (foreground) at room temperature, captured simultaneously with three orthogonal views (background) that were calculated from the nine BGW wavelength shifts.

Figure 7(a) (Media 2, 0 to 50 s) shows a time sequence of the calculated fiber shape (top) together with the dynamically changing reflection spectrum (bottom) recorded from the fiber sensor under variable bending at room temperature. Each Bragg resonance in the reflection spectrum is initially identified by arrows to the physical location of the BGW in the fiber as highlighted by boxes. In the reflection spectrum, the red lines mark the unstrained and room-temperature Bragg wavelengths with the BGWs in each sensing arm (i.e. center and side) further labeled by a different color. As expected during fiber bending, large wavelength shifts of up to \( \sim 560 \) pm are observed in the off-center BGWs relative to the non-shifting center BGWs,
corresponding to a minimum bend radius of 75 mm.

Simultaneous sensing of fiber shape and temperature is also presented in Fig. 7(b) (Media 2, 50 to 255 s) for non-uniform bending and heating of the fiber sensor with a hot iron. Temperature in the range of 24 to 100 °C was calculated to ±5 °C precision from the wavelength shift of the center BGWs and linear interpolated in between each axially co-located BGW triplet. Assuming uniform temperature in the fiber’s cross section, the fractional wavelength shifts of the center and side arm BGWs were temperature-corrected to provide the distributed fiber strain values, and thus offer the real-time measure of the temperature gradient seen along the fiber in false color together with the fiber sensor shape in Media 2. The BGW spectra were also found to broaden into a spectral chirp when heated at a point smaller than the 1 cm long BGW length, which could be used to give more precise information of thermal gradients forming within the grating [30].

Fig. 7. Single frame images from a time sequence (Media 2) of fiber shape and temperature profile (top) calculated from the Bragg wavelength shifts in the reflection spectrum of nine BGWs (bottom), where the red lines indicate the Bragg wavelengths of unstrained gratings at room temperature. Fiber bending under uniform (a) and graded (b) temperature.

5. Discussion

The present fiber sensor design (Fig. 1) offers several technical advantages over other shape sensors that have been based on FBGs deployed in either multiple optical fibers [31, 32] or multicore optical fiber [10, 11]. The 3D shape sensing demonstrated here serves as a more flexible, lightweight, and compact device than possible with assemblies of multiple optical fibers that must be precisely arranged and typically require bonding to a host structure. The distributed BGW array, laser-written inside a single coreless fiber to less than 2 µm alignment accuracy, ensured accurate radial, azimuthal, and axial alignment of the co-located BGWs, all within a single fiber. The freestanding design enables shape sensing by conforming to a flexing object without the need for hard bonding in typical FBG strain sensing applications. This advantage opens opportunities for sensing in catheters, for example, where a free-moving fiber sensor can offer catheter guidance from within the catheter lumen and be repositioned for administering drugs or passing other instruments. In this way, high resolution bend, shape, and temperature sensing was demonstrated without the laborious alignment, bonding, calibration, and packaging steps otherwise required in multiple optical fiber sensing assemblies. The present device provided ±1.1 × 10⁻³ mm⁻¹ precision in curvature, 0.6 mm accuracy in position (i.e. 1.1%
lateral position error per unit length), and ±5 °C precision in temperature measurements that were limited by the polarization splitting error in the BGW birefringence. Shape sensing with FBG-embedded MCFs have been demonstrated with similar benefits; for example, the state-of-the-art MCF device in [11] yielded the same lateral position accuracy of 1% per unit length. However, facile optical coupling to each of the MCF fiber cores has proven technically challenging. In the present work, the 3D laser writing of a 1 × 3 directional coupler was a major advantage to multiplex all nine BGW sensors for convenient coupling to a single-core SMF.

Femtosecond laser direct writing of optical waveguides and BGWs in the fused silica fiber without the need for photosensitive response provides several benefits such as rapid prototyping of sensor design, flexible waveguide arrangement, compact 3D integration and multiplexing of many sensor elements. However, the present device is limited by waveguide propagation loss of ~0.5 dB/cm to enable distributed fiber sensing in devices of up to only 15 cm length for the current 10–15 dB grating strength of BGWs, whereas a much longer (up to 1.7 m) shape sensor has been demonstrated with FBGs formed in low-loss MCF [11]. While stronger gratings and lower spectral noise can improve this length, a femtosecond laser approach to write couplers between the waveguide cores in a MCF together with distributed FBGs maybe more attractive to combine the benefits of flexible 3D laser writing and low-loss MCF waveguide. In this way, simultaneous interrogation of all the waveguide cores will be possible through a single waveguide port as demonstrated with the present fiber sensor.

6. Conclusion

A temperature-compensated fiber-optic 3D shape sensor was designed and fabricated by femtosecond laser direct writing of various optical components in a coreless optical fiber. The 3D formation of a 1 × 3 coupler was instrumental in facilitating efficient and nearly balanced light coupling and collection from the laser-written optical circuit elements for convenient interrogation through a fusion-spliced SMF. This approach offered advantages in facile and flexible fabrication in comparison with prior demonstrations of shape sensors that were based on FBGs in multiple-fiber assemblies [31, 32] or in a MCF [10, 11]. The geometry of the nine axially and radially distributed BGW sensors enabled decoupling of the Bragg wavelength shifts for simultaneous strain and temperature measurements on which to infer real-time shape and thermal profile along the fiber length. The fiber sensor was calibrated for bend sensing up to $2.5 \times 10^{-2}$ mm$^{-1}$ curvature, temperature sensing up to 250 °C, and real-time dynamic 3D fiber shape sensing with positional error of ~0.6 mm. The overall compact size and high temperature tolerance make the present fiber sensor attractive for structural, industrial, reactor, and pipeline applications as well as for integration into biomedical and catheter devices.

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