



OFDR-based shape sensor using a plane-by-plane-inscribed weak FBG array in multicore fiber

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Abstract: An OFDR-based shape sensor was demonstrated using a weak fiber Bragg grating (WFBG) array inscribed in multicore fiber (MCF) by a femtosecond-laser plane-by-plane technique. An integrated modulation plane, consisting of a central square region and a concentric annular region, was introduced to simultaneously modulate multiple cores without precise core-by-core alignment. At a laser-focused scanning speed of 0.5 mm/s, one WFBG consisting of 10 integrated modulation planes could be fabricated within 35 s. After optimization of the inscription energy, grating order, and modulation plane number, a 60-cm-long WFBG array containing 60 gratings with a spacing of 1 cm was fabricated in the MCF and interrogated using OFDR. The fabricated sensor achieved relative reconstruction errors of 1.41% and 1.95% in 2D and 3D shape sensing, respectively.

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1. Introduction

Optical fiber shape sensing has attracted considerable attention in minimally invasive intervention [1,2], aerospace systems [3], and robotics [4], where accurate 2D and 3D shape reconstruction is required. Among various implementations, multicore fibers (MCFs) are particularly attractive because the strain responses of spatially separated cores enable recovery of curvature, bending direction, and 3D shape [5,6]. MCF-based shape sensing has been widely recognized as a promising approach for distributed or quasi-distributed vector bending measurement. Optical frequency domain reflectometry (OFDR)-based shape sensing offers high spatial resolution and high strain sensitivity [7–9]. OFDR-based shape sensing in MCFs has been demonstrated using either intrinsic scattering or laser-enhanced scattering structures, such as femtosecond-laser-induced permanent scatter arrays [10] and weak fiber Bragg grating (WFBG) arrays [11]. For OFDR-based MCF shape sensors, the efficient fabrication of high-quality WFBG arrays remains a key issue.

Phase-mask-based inscription features a simple setup and high fabrication efficiency, but its flexibility is restricted by the fixed phase-mask period and it usually requires hydrogen loading [12] or other photosensitivity-enhancement pretreatments [13]. In contrast, femtosecond-laser inscription provides much higher flexibility in wavelength and structure design, which is advantageous for WFBG array fabrication and parameter optimization in MCF [14,15]. In particular, femtosecond-laser plane-by-plane inscription has been demonstrated as an effective approach for fabricating ultrahigh-order FBGs with flexible spectral design [16]. Separately, this technique has also been used for MCF-based FBG shape sensing. Bronnikov et al. demonstrated

a durable shape sensor based on an FBG array inscribed in a polyimide-coated 7-core fiber [17], and Paloschi et al. investigated real-time 3D shape reconstruction using MCF FBG arrays [18]. However, many reported MCF-FBG shape sensors are WDM-based quasi-distributed sensors, whose multiplexing capacity is limited by the available spectral range and the number of distinguishable wavelength channels. In addition, MCF FBG array fabrication generally requires core identification, alignment, and inscription, making the process relatively complex and time-consuming for long WFBG arrays. Adaptive parallel inscription assisted by spatial light modulation has also been reported, showing high flexibility and consistency, although at the expense of increased system complexity and calibration burden [19].

In this work, we propose and demonstrate an OFDR-based shape sensor using a WFBG array inscribed in MCF by femtosecond-laser plane-by-plane technique. Different from conventional core-by-core inscription, an integrated modulation plane consisting of a central square region and a concentric annular region was used to simultaneously modulate multiple cores. The effects of inscription energy, grating order, and plane number on the reflection spectrum and insertion loss were systematically investigated. Using the optimized parameters, a 60 cm-long WFBG array with 60 gratings at 1 cm spacing was fabricated for shape sensing. 2D and 3D shape sensing experiments were further carried out to validate the performance of the fabricated WFBG array in MCF.

2. Fabrication and measurement experimental setup

2.1. Plane-by-plane inscription of WFBG array in MCF

A femtosecond laser (Pharos, Light Conversion) operating at 515 nm with a pulse width of 290 fs and a repetition rate of 200 kHz was used to inscribe the WFBG array in MCF by the plane-by-plane technique, as shown in Fig. 1(a). The MCF (SM-6.5-42-150, YOEC) comprises a central core, i.e., Core1, and six outer cores, i.e., Core2 to Core7, hexagonally arranged around it. All cores have a diameter of 6.5 μm , i.e., $d = 6.5 \mu\text{m}$, and the spacing between Core1 and each outer core is 42 μm , i.e., $R_0 = 42 \mu\text{m}$.

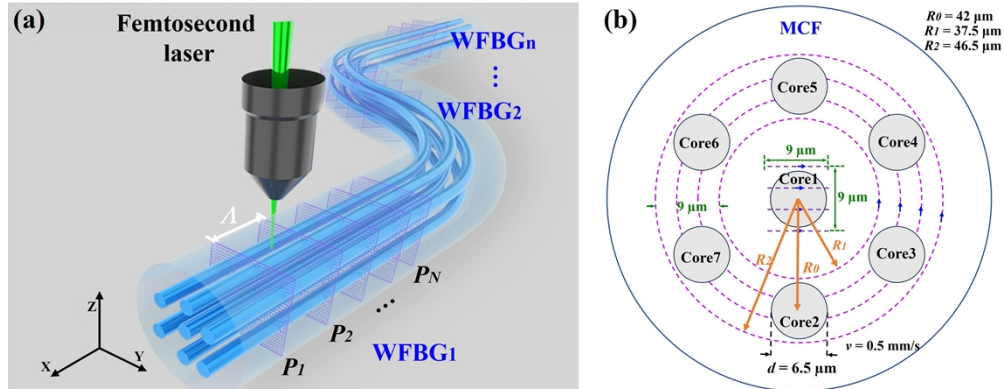


Fig. 1. Schematic of femtosecond-laser plane-by-plane inscription of a WFBG array in MCF. (a) fabrication process of the WFBG array in MCF, where each WFBG consists of N modulation planes, i.e., $P_1, P_2, \dots, P_N$, with a pitch of Λ ; (b) Cross-sectional design of one integrated modulation plane. A 9 μm square region is written over Core1, while an annular region from $R_1 = 37.5 \mu\text{m}$ to $R_2 = 46.5 \mu\text{m}$ is written to cover the six outer cores. The dashed lines indicate the femtosecond-laser scanning trajectories in the y - z plane, with a scanning speed of $v = 0.5 \text{ mm/s}$.

The fabrication procedure of WFBGs in MCF using the plane-by-plane technique is described as follows. Step1, the MCF was clamped by a pair of fiber holders mounted on a 3D air-bearing translation stage, which controlled the relative position between the femtosecond laser focus and the MCF. The x -axis was defined as the fiber axis, while the y - z plane corresponded to the fiber cross-section. Step2, the femtosecond laser focus was first positioned at the center of Core1, i.e., the central core, as the processing origin. It then raster-scanned the square region over Core1, schematically represented by four parallel lines in Fig. 1(b), to form a square modulation plane with a side length of $9\ \mu\text{m}$. The laser was switched on during writing paths and switched off during flyback paths. Step3, the laser focus was then moved to the annular region and scanned along concentric circular trajectories from $R_1 = 37.5\ \mu\text{m}$ to $R_2 = 46.5\ \mu\text{m}$, completing one integrated modulation plane. The annular width of $9\ \mu\text{m}$, larger than the core diameter of $6.5\ \mu\text{m}$, enabled effective modulation without precise core-by-core alignment. Here, the inscription speed $v = 0.5\ \text{mm/s}$ denotes the laser-focus scanning speed used for writing the square and annular regions in the y - z plane. Step 4, the MCF was translated along the x -axis by one grating pitch Λ after each modulation plane was fabricated, and Steps 2 and 3 were repeated to form $P_1, P_2, \dots, P_N$. Thus, one WFBG consisting of N integrated modulation planes was obtained. Step 5, the above process was repeated at different axial positions to fabricate a WFBG array in the MCF. A single WFBG consisting of 10 modulation planes could be fabricated within 35 s, as shown in Visualization 1 of the Supplementary Material.

2.2. OFDR-based experimental setup

As shown in Fig. 2, a conventional OFDR system was constructed to measure the reflected signals from each core of WFBG-array-inscribed MCF. The light from a tunable laser source (TLS, N7776C, Keysight) was split by optical coupler, i.e., OC_1 , into an auxiliary interferometer (AI) and a main interferometer (MI). The sweep range and sweep speed of the TLS were 1540-1560 nm and 40 nm/s, respectively. The AI consisted of two Faraday rotating mirrors, i.e., FRM_1 and FRM_2 , and a 51.5 m delay fiber, which was used to provide the synchronization clock for data acquisition and sweep linearization. In the MI, the light was further divided into a reference arm and a measurement arm through OC_2 . The polarization state in the reference arm was adjusted by a polarization controller (PC), while the measurement light was launched into the WFBG-array-inscribed MCF. The reflected signals were recombined with the reference light through OC_3 and then separated into the P- and S-polarization components by two polarization beam splitters, i.e., PBS_1 and PBS_2 . The beat signal from the AI was detected by balanced photodetector (BPD_1 , 480C, Thorlabs), while the two interference signals from the MI were detected by BPD_2 and BPD_3 , respectively, and then acquired by a data acquisition card (PCI-6115, NI). Each core of the MCF was sequentially interrogated using a fan-in/fan-out and a 1×8 mechanical optical switch.

3. Optimization of the fabrication parameters of the WFBG array in MCF using plane-by-plane inscription technique

3.1. Inscription energy

To find an appropriate inscription energy for fabricating WFBG in MCF using femtosecond-laser plane-by-plane technique, a relatively low inscription energy of 13 nJ was first employed. Under the grating order of 2 and plane number of 100, i.e., $m = 2, N = 100$, periodic reflection peaks could be clearly observed in the distance-domain spectra of Core1, Core2, and Core5, indicating that grating inscription was achieved at the designed positions, as shown in Fig. 3(a). However, the reflection peaks of Core2, which was farther from the laser irradiation side, were much weaker than those of Core5 and Core1, which were closer to the laser irradiation side. This indicated that the refractive-index modulation induced in Core2 was insufficient at 13 nJ.

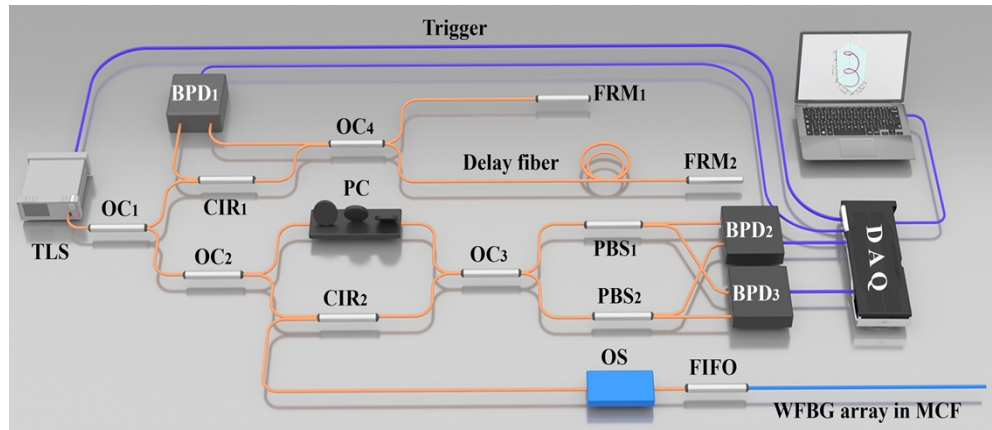


Fig. 2. Experimental setup of the OFDR-based shape sensing based on a WFBG array inscribed in MCF by the femtosecond-laser plane-by-plane technique. TLS: tunable laser source; OC: optical coupler; CIR: circulator; BPD: balanced photodetector; FRM: Faraday rotation mirror; PC: polarization controller; PBS: polarization beam splitter; DAQ: data acquisition card; OS: optical switch; FIFO: fan-in/fan-out.

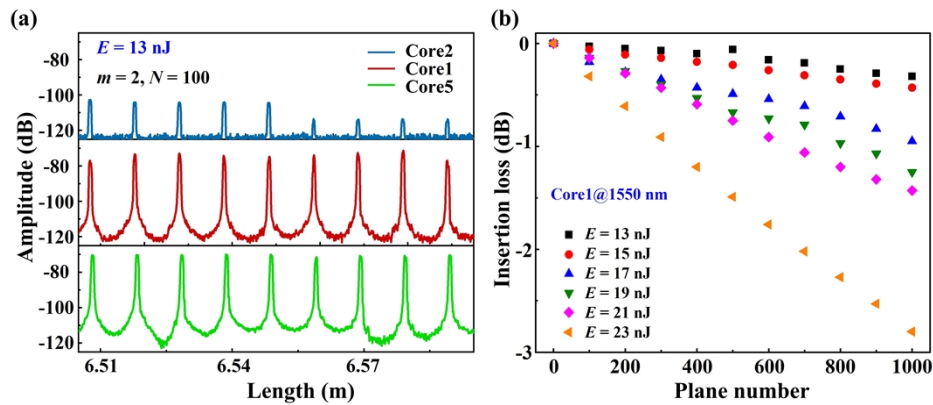


Fig. 3. (a) Distance-domain spectra of Core2, Core1, and Core5 for the WFBG fabricated at an inscription energy of 13 nJ with $m = 2$ and $N = 100$, showing the weaker reflection peaks of Core2 due to insufficient refractive-index modulation; (b) insertion loss (IL) of the central core, i.e., Core1, at 1550 nm as a function of plane number under inscription energies of 13, 15, 17, 19, 21, and 23 nJ, respectively.

Since increasing the inscription energy could improve the far-side core inscription but simultaneously increase the insertion loss (IL), the IL was further investigated as a function of plane number under different inscription energies. The outer cores could not be perfectly aligned in each experiment, whereas the central core, i.e., Core1, provided the best repeatability. Therefore, the distance domain spectrum and reflection spectrum of Core1 was selected to optimize the inscription parameter for the subsequent experiment. For a given inscription energy, the IL at 1550 nm increased with the number of planes, as shown in Fig. 3(b). For example, at 15 nJ, the IL increased from 0 dB to about 0.2 dB at 500 planes and further to about 0.5 dB at 1000 planes. A similar trend was also observed at other inscription energies, while the IL increase became much more pronounced at higher energy. In addition, for a fixed plane number, the IL increased with inscription energy. For instance, at 500 planes, the IL increased from about 0.1 dB

at 13 nJ to approximately 1.5 dB at 23 nJ, while at 1000 planes it further increased from about 0.35 dB to nearly 2.8 dB. These indicated that the IL was strongly dependent on the inscription energy and plane number. Therefore, the inscription energy of 15 nJ, i.e., $E = 15$ nJ, was chosen as a compromise between low IL and reliable multicore inscription.

3.2. Grating order and plane number

To further investigate the effect of the modulation plane number, i.e., N , on the spectral characteristics of WFBG in MCF, 2nd-order and 50th-order WFBGs, i.e., $m = 2$ and 50, were fabricated and compared. Note that the Bragg wavelength was fixed at 1550 nm for both cases, i.e., $\lambda_B = 1550$ nm. For the 2nd-order in Core1, as the plane number, i.e., N , was increased from 20 to 50, 100, 200 and 300, the 3-dB bandwidth was reduced to 14.2 nm, 7.0 nm, 3.4 nm, and 2.3 nm, respectively, as shown in Fig. 4(a). For the 50th-order, a similar narrowband effect was achieved with much fewer modulation planes, as shown in Fig. 4(b).

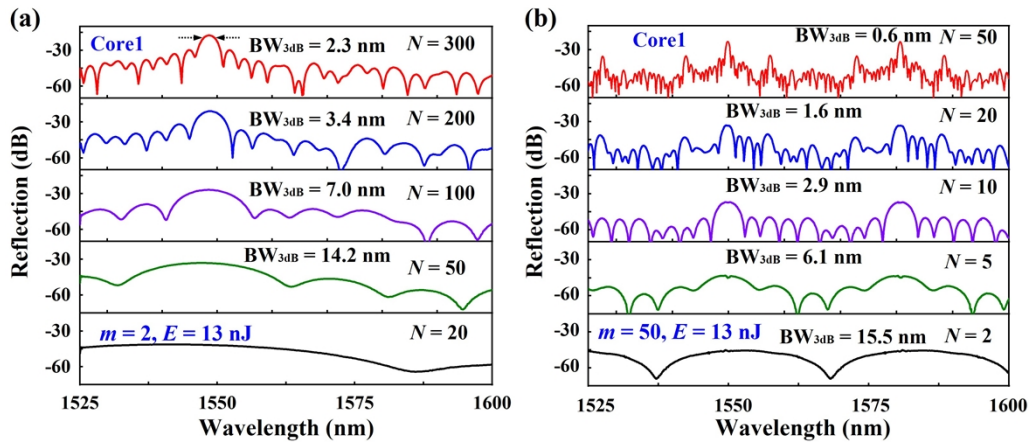


Fig. 4. Reflection spectra of WFBG fabricated in the Core1 of the MCF by the femtosecond-laser plane-by-plane technique under different modulation plane numbers. (a) 2nd-order WFBG, i.e., $m = 2$, with $N = 20, 50, 100, 200$, and 300; (b) 50th-order WFBG, i.e., $m = 50$, with $N = 2, 5, 10, 20$, and 50. Note that the Bragg wavelength was fixed at 1550 nm in both cases.

Specially, as N increased from 2 to 5, 10, 20, and 50, the 3-dB bandwidth decreased from 15.5 to 6.1, 2.9, 1.6, and 0.6 nm, respectively. This indicated that increasing the plane number could effectively compress the reflection bandwidth, attributing to the increase in effective grating length with plane number [20]. Moreover, high-order WFBG was more efficient in achieving narrowband reflection, since the 2nd-order WFBG required $N = 300$ to reach 2.3 nm, whereas the 50th-order WFBG already exhibited a comparable value of 2.9 nm at $N = 10$, which further decreased to 1.6 nm at $N = 20$. This indicated that increasing the grating order could enable a much narrower reflection spectrum to be obtained with fewer modulation planes, which was beneficial for improving fabrication efficiency.

With the plane number fixed at $N = 10$, the reflection spectra of WFBGs with different high orders were further compared. When the WFBG order was further increased from 100 to 300, pronounced periodic parasitic peaks gradually appeared in the reflection spectra in addition to the target Bragg reflection peak, as shown in Fig. 5. Meanwhile, the spacing between adjacent parasitic peaks was decreased from 15.2 nm to 7.6 nm and 5.0 nm, respectively, indicating that the parasitic peaks became significantly denser with increasing grating order. The Fabry–Perot (FP) microcavity formed between two reflective modulation units gave rise to periodic interference

peaks, with these parasitic peaks originating from FP interference between adjacent modulation planes [21]. The free spectral range (FSR) of the FP cavity could be expressed as

$$FSR = \frac{\lambda_B^2}{2n\Lambda} \quad (1)$$

where λ_B is the Bragg wavelength, i.e., 1550 nm, n is the effective refractive index, and Λ is the spacing between adjacent modulation planes. Therefore, for a higher-order WFBG, i.e., a larger spacing between adjacent modulation planes, the FSR was decreased, resulting in a reduced spacing between neighboring parasitic peaks and a denser peak distribution within a limited wavelength range. This indicated that, although increasing the WFBG order could enhance the narrowband effect, an excessively high grating order introduced stronger FP-induced parasitic interference, which was unfavorable for subsequent wavelength demodulation. Considering the trade-off between spectral narrowing and suppression of FP-induced spectral interference, the 100th-order, i.e., $m = 100$, was selected for the subsequent experiments.

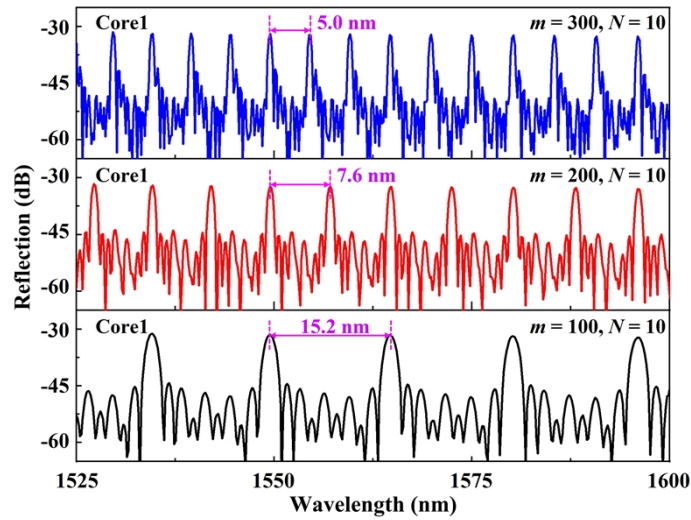


Fig. 5. Reflection spectra of WFBG fabricated in Core1 of the MCF with grating orders of 100, 200, and 300 at a fixed plane number of $N = 10$. As the WFBG order increased, the spacing between adjacent periodic Fabry-Perot parasitic peaks decreased from 15.2 to 7.6 and 5.0 nm, respectively.

After identifying the order, i.e., $m = 100$, the effect of the plane number on the reflection spectral characteristics was further investigated. As the plane number increased from $N = 5$ to 10, 15, 20, 25, and 30, the main reflection peak gradually became narrower, with the corresponding 3-dB bandwidths decreasing from 2.5 to 1.3, 0.9, 0.6, 0.5, and 0.4 nm, respectively, as shown in Fig. 6. It is evident that the bandwidth compression effect was more pronounced at relatively small plane numbers. For example, when N increased from 5 to 20, the bandwidth decreased rapidly from 2.5 nm to 0.6 nm; in contrast, when N was further increased to 25 and 30, the bandwidth was only slightly reduced to 0.5 and 0.4 nm, respectively. This indicated that the marginal improvement in bandwidth gradually diminished as the plane number continued to increase. Therefore, considering the trade-off between spectral performance and inscription cost, $N = 20$ was finally selected.

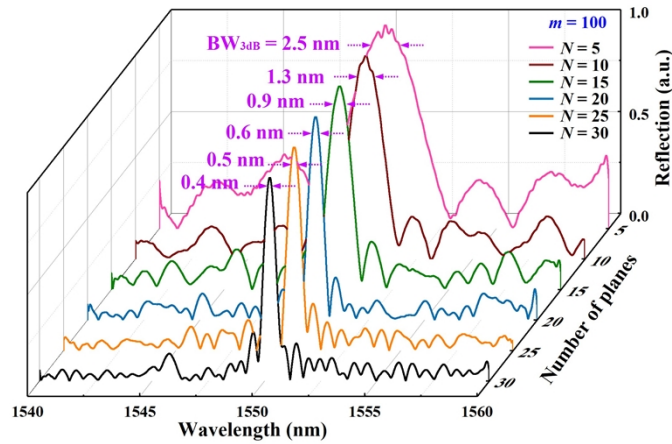


Fig. 6. Reflection spectra of the 100th-order WFBG with different numbers of modulation planes ($N = 5$ to 30). As N increased, the corresponding 3-dB bandwidth decreased from 2.5 nm to 1.3 nm, 0.9 nm, 0.6 nm, 0.5 nm, and 0.4 nm, respectively.

3.3. Fabrication of WFBG array in MCF

Under the optimized inscription parameters of $E = 15$ nJ, $m = 100$, and $N = 20$, a 60-cm-long WFBG array with an IL of 0.52 dB was successfully inscribed in the MCF using the plane-by-plane technique. The reflected signals from each core are acquired using the OFDR system shown in Fig. 2 and transformed into the spatial domain by FFT. As shown in Fig. 7(a), periodically distributed enhanced-scattering peaks were observed in all seven cores. The average enhanced-scattering levels of Core1 to Core7 were 45.6 ± 3.7 dB, 35.2 ± 6.3 dB, 39.3 ± 3.9 dB, 38.7 ± 4.8 dB, 48.5 ± 5.0 dB, 50.0 ± 3.6 dB, and 36.0 ± 4.1 dB, respectively. Here, the enhanced-scattering level was defined as the amplitude difference between the WFBG peak and the local noise floor. All cores showed scattering enhancement higher than 30 dB. The cores closer to the laser-incident side, such as Core5, Core6, and Core1, exhibited stronger reflections, whereas the far-side cores, such as Core2, Core3, and Core7, showed weaker reflections. To reconstruct the local spectra, a sliding window with a length of $N = 128$ sampling points was used to extract the localized signal around each WFBG. The windowed signal was zero-padded to 16384 points and transformed back to the spectral domain by IFFT. As shown in Fig. 7(b), the reconstructed spectra of WFBG₂₀ in Core1, Core5, and Core6 exhibited distinct narrowband Bragg peaks around 1550 nm, with a 3-dB bandwidth of approximately 0.6 nm, confirming the good spectral quality of the inscribed WFBGs.

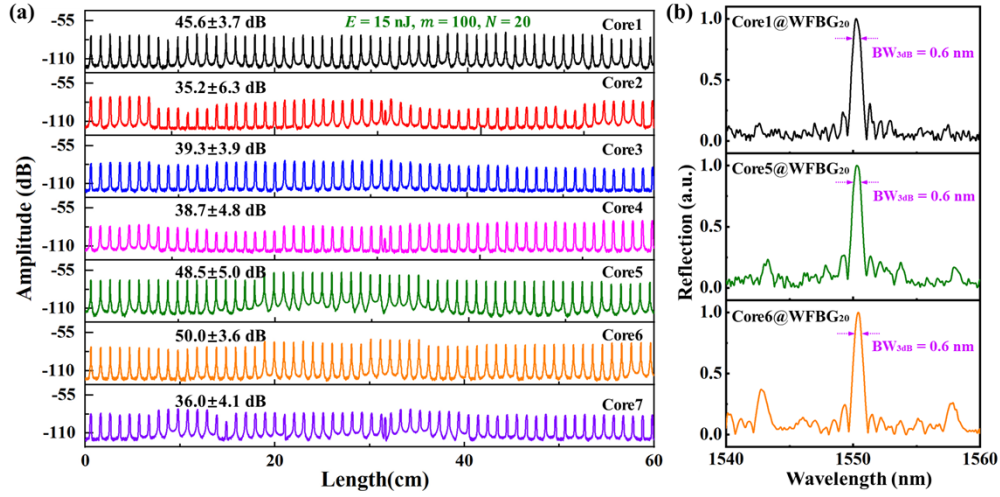


Fig. 7. (a) Distance-domain enhanced-scattering peaks of the 60-cm-long WFBG array inscribed in the MCF using the femtosecond-laser plane-by-plane method under the optimized inscription parameters of $E = 15$ nJ, $m = 100$, and $N = 20$, with a spacing of 1 cm; (b) Reflection spectra of the WFBG in Core1, Core5, and Core6, showing narrowband Bragg peaks around 1550 nm.

4. 2D and 3D shape sensing

4.1. Principle of shape reconstruction

Based on the OFDR demodulation described above, the localized reflection spectrum of each WFBG can be reconstructed, and the corresponding Bragg wavelength shift $\Delta\lambda_i(s)$ can be obtained at each sensing node. These wavelength shifts are then converted into axial strains of different cores, from which the local curvature, bending direction, and three-dimensional shape are further reconstructed.

The Bragg wavelength shift is approximately linearly proportional to the local axial strain. Thus, the strain of the i -th core is calculated as

$$\varepsilon_i(s) = \frac{\Delta\lambda_i(s)}{S_{\varepsilon,i}} \quad (2)$$

where $\Delta\lambda_i(s)$ and $S_{\varepsilon,i}$ are the Bragg wavelength shift and calibrated strain sensitivity of the i -th core, respectively. To suppress common-mode effects caused by temperature variation and global axial stretching, the central core is used as a reference. The differential strain of the i -th outer core is given by

$$\Delta\varepsilon_i(s) = \varepsilon_i(s) - \varepsilon_0(s) \quad (3)$$

where $\varepsilon_0(s)$ is the strain measured by the central core. Based on the Euler–Bernoulli beam theory, the fiber cross-section is assumed to remain planar and perpendicular to the neutral axis during bending. Therefore, the differential strain of the i -th outer core can be expressed as

$$\Delta\varepsilon_i(s) = \kappa(s) \cdot R_i \cos(\theta_b(s) - \theta_i) \quad (4)$$

where $\kappa(s)$ is the local curvature, R_i is the radial distance from the i -th outer core to the central core, i.e., $R_i = 42$ μm , $\theta_b(s)$ is the bending direction angle, and θ_i is the azimuthal angle of the i -th outer core in the fiber cross-section. Two non-collinear outer cores, i.e., Core5 and Core6, are selected to provide independent sensing vectors. By solving the corresponding equations,

the curvature $\kappa(s)$ and bending direction $\theta_b(s)$ could be uniquely determined at each localized sensing node, i.e., each WFBG.

For three-dimensional shape reconstruction, a Bishop frame is adopted to avoid singularities and discontinuities of the normal vector when the curvature approaches zero [22]. The curvature is decomposed into two orthogonal components in the Bishop frame as [23]

$$\begin{cases} \kappa_1(s) = \kappa(s) \cdot \cos\theta_b(s), \\ \kappa_2(s) = \kappa(s) \cdot \sin\theta_b(s). \end{cases} \quad (5)$$

The evolution of the Bishop frame is governed by

$$\begin{bmatrix} T'(s) \\ N_1'(s) \\ N_2'(s) \end{bmatrix} = \begin{bmatrix} 0 & \kappa_1(s) & \kappa_2(s) \\ -\kappa_1(s) & 0 & 0 \\ -\kappa_2(s) & 0 & 0 \end{bmatrix} \begin{bmatrix} T(s) \\ N_1(s) \\ N_2(s) \end{bmatrix} \quad (6)$$

where $T(s)$ is the unit tangent vector, and $N_1(s)$ and $N_2(s)$ are two orthogonal normal vectors. The above differential equations are solved using a fourth-order Runge–Kutta method, with the OFDR spatial sampling interval Δs as the integration step. Finally, the three-dimensional position of the fiber is reconstructed by integrating the tangent vector along the arc length,

$$r(s) = r(0) + \int_0^s T(s) ds \quad (7)$$

where $r(0)$ is the initial anchored position, which is set as the origin of the global coordinate system. This procedure yields the absolute spatial coordinates of each node along the fiber in the three-dimensional Cartesian coordinate system.

4.2. Influence of spectral bandwidth on shape sensing performance

The influence of spectral bandwidth on the bending radius reconstruction was first investigated. The WFBGs with different spectral bandwidths, as shown in Fig. 8, were tested on a curvature plate with a bending radius of 5 cm, and each sample was repeatedly measured 25 times. As shown in Fig. 8, the reconstructed bending radius became more stable and closer to bending radius of 5 cm as the spectral bandwidth narrows. Specifically, when $N = 5$, the reconstructed bending radius varied from 2.81 to 8.07 cm, showing large fluctuations. In contrast, when $N = 30$, the reconstructed bending radius was limited to 4.92–5.04 cm, showing significantly improved stability. These results indicate that a narrower spectral bandwidth provides a more stable and well-defined spectral response, which improves the accuracy of wavelength-shift extraction during OFDR demodulation.

4.3. 2D shape sensing

Using the fabricated WFBG array in Fig. 7, 2(D) shape sensing experiments were carried out to verify its shape sensing capability. As shown in Fig. 9(a), the WFBG array was sequentially placed on curvature plates with different radii of 5, 7, 9, 11, 13, and 15 cm. According to Eqs. (2) and (3), the Bragg wavelength shifts measured from Core1, Core5, and Core6 were converted into differential strains. The local curvature and bending direction at each WFBG node were then calculated using Eq. (4). The corresponding curvature distributions were presented in Fig. 9(b). In all cases, the bending region could be clearly identified, and the reconstructed curvature decreased monotonically with increasing bending radius. The average peak curvature values were 19.78, 13.98, 10.94, 8.93, 7.52, and 6.54 m^{-1} for bending radii of 5, 7, 9, 11, 13, and 15 cm, respectively, which agreed well with the theoretical trend of $1/R$.

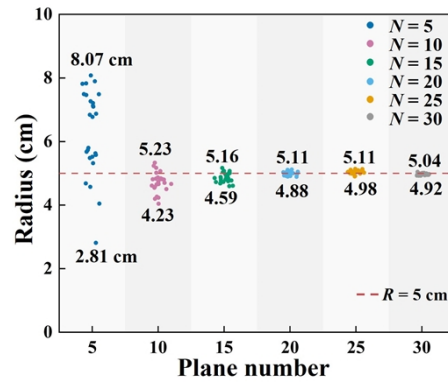


Fig. 8. Reconstructed bending radii of WFBGs with different numbers of grating planes under a bending radius of 5 cm. Each sample was repeatedly measured 25 times. The red dashed line represents the preset bending radius.

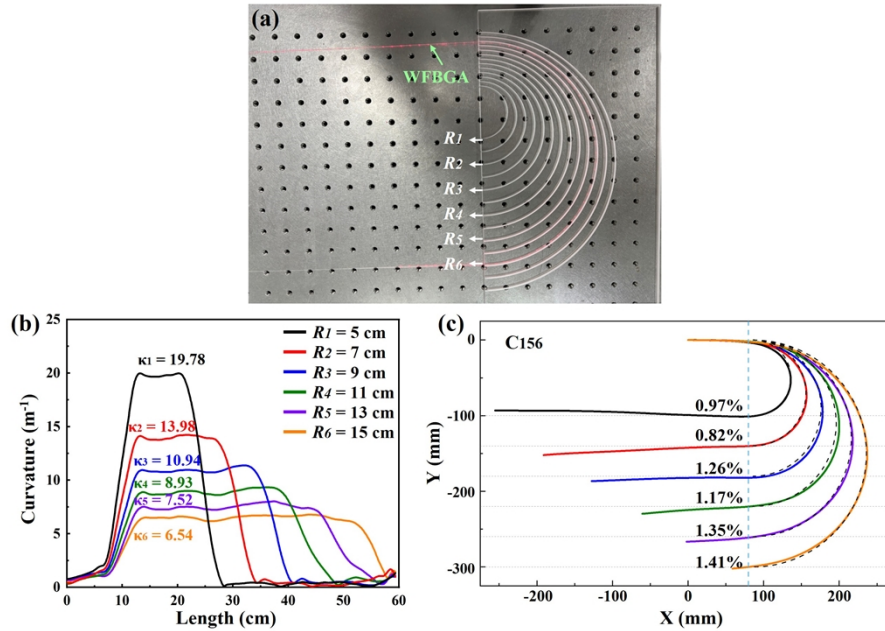


Fig. 9. (a) Experimental setup for 2D shape sensing using the femtosecond-laser plane-by-plane-inscribed WFBG array placed on curvature plates with bending radii of 5, 7, 9, 11, 13, and 15 cm; (b) reconstructed curvature distributions for different radii; (c) corresponding 2D reconstructed shapes and relative errors.

Moreover, the position and range of the high-curvature region were consistent with the actual bending region of the curvature plate, indicating that the fabricated WFBG array could accurately demodulate the curvature magnitude and bending position. Considering relatively strong reflection peaks and stable spectral responses, Core1, Core5, and Core6 were selected for curvature estimation. Based on the curvature and bending direction obtained from Eq. (4), the corresponding 2D shapes were further reconstructed using the Bishop-frame method described by Eqs. (5)–(7), as shown in Fig. 9(c). The relative reconstruction error is defined as the normalized end-point error [24]:

$$\text{Relative error} = \frac{\|P_{\text{end}}^{\text{rec}} - P_{\text{end}}^{\text{ref}}\|}{L_{\text{eff}}} \times 100\% \quad (8)$$

where $P_{\text{end}}^{\text{rec}}$ and $P_{\text{end}}^{\text{ref}}$ are the reconstructed and reference end-point positions, respectively, and $L_{\text{eff}} = 60$ cm is the effective sensing length, corresponding to the length of fabricated WFBG array. The reconstructed fiber profiles agreed well with the preset bending trajectories, with relative errors of 0.97%, 0.82%, 1.26%, 1.17%, 1.35%, and 1.41% for bending radii of 5, 7, 9, 11, 13, and 15 cm, respectively. All errors were below 1.5%, confirming the good 2D shape reconstruction accuracy of the fabricated WFBG array.

4.4. 3D shape sensing

To further evaluate the 3D shape sensing capability of the fabricated WFBG array, the sensor was arranged along the helical groove on the surface of a cylindrical structure, as shown in Fig. 10(a). The cylinder had a diameter of $D = 8.7$ cm, a generatrix height of $h = 20.2$ cm, and a helical pitch of $p = 10.1$ cm. According to the geometric relation of the helical trajectory, the theoretical bending radius could be expressed as

$$\rho_{\text{theory}} = R \left[1 + \left(\frac{p}{2\pi R} \right)^2 \right] \quad (9)$$

where $R = D/2 = 4.35$ cm is the cylinder radius. By substituting the above parameters, the theoretical bending radius, i.e., ρ_{theory} , was calculated to be 4.94 cm. The reconstructed curvature and radius distributions were shown in Fig. 10(b). It could be seen that both quantities remained nearly constant over the effective sensing region, with an average curvature of 20.65 m^{-1} , i.e., $\overline{\kappa} = 20.65 \text{ m}^{-1}$ and an average reconstructed radius of 4.84 cm, i.e., $\overline{R} = 4.84$ cm, in good agreement with the theoretical value. Moreover, the recovered curvature and bending direction were used as inputs for the Bishop-frame integration described by Eqs. (5)–(7), yielding the 3D spatial trajectory shown in Fig. 10(c). The reconstructed 3D helical profile agreed well with the theoretical trajectory, where the relative error was 1.95%.

5. Conclusion

In conclusion, we have proposed and demonstrated an OFDR-based shape sensor using a WFBG array inscribed in MCF by femtosecond-laser plane-by-plane technology. For the 100th-order WFBG, the 3-dB bandwidth decreased from 2.5 nm to 0.4 nm as the plane number increased from 5 to 30, while the bandwidth-narrowing effect gradually saturated at large plane numbers. Further increasing the grating order led to denser Fabry–Perot-induced parasitic peaks, with the adjacent peak spacing decreasing from 15.2 nm to 7.6 nm and 5.0 nm for the 100th-, 200th-, and 300th-order WFBGs, respectively. Together with the IL analysis, the optimized parameters were $E = 15$ nJ, $m = 100$, and $N = 20$. Under these conditions, a 60-cm-long WFBG array with 60 gratings at 1 cm spacing was successfully fabricated in the MCF. In 2D shape sensing, the reconstructed peak curvatures followed the theoretical $1/R$ trend for bending radii from 5 to 15 cm, with relative reconstruction errors below 1.5%. In the 3D shape sensing, the reconstructed average bending radius was 4.84 cm, close to the theoretical value of 4.94 cm, with a relative

error of 1.95%. These results demonstrate a practical route for fabricating WFBG array in MCF and highlight their potential for OFDR-based 2D/3D shape sensing.

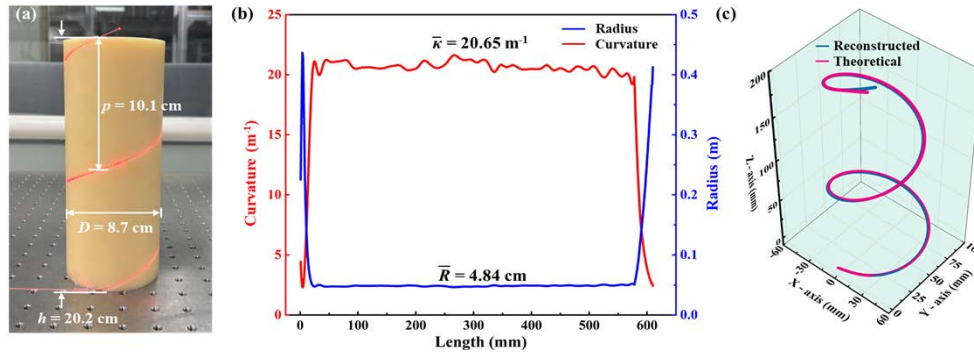


Fig. 10. (a) Experimental setup for 3D shape sensing using the femtosecond-laser plane-by-plane-inscribed WFBG array arranged along the helical groove on a cylindrical surface with $D = 8.7$ cm, $h = 20.2$ cm, and $p = 10.1$ cm; (b) reconstructed curvature and radius distributions along the sensing length; (c) comparison of the reconstructed 3D helical profile with the theoretical trajectory.

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