Supplementary information

Single-fiber three-dimensional shape sensing via femtosecond laser inscribed orthogonal eccentric scatterers

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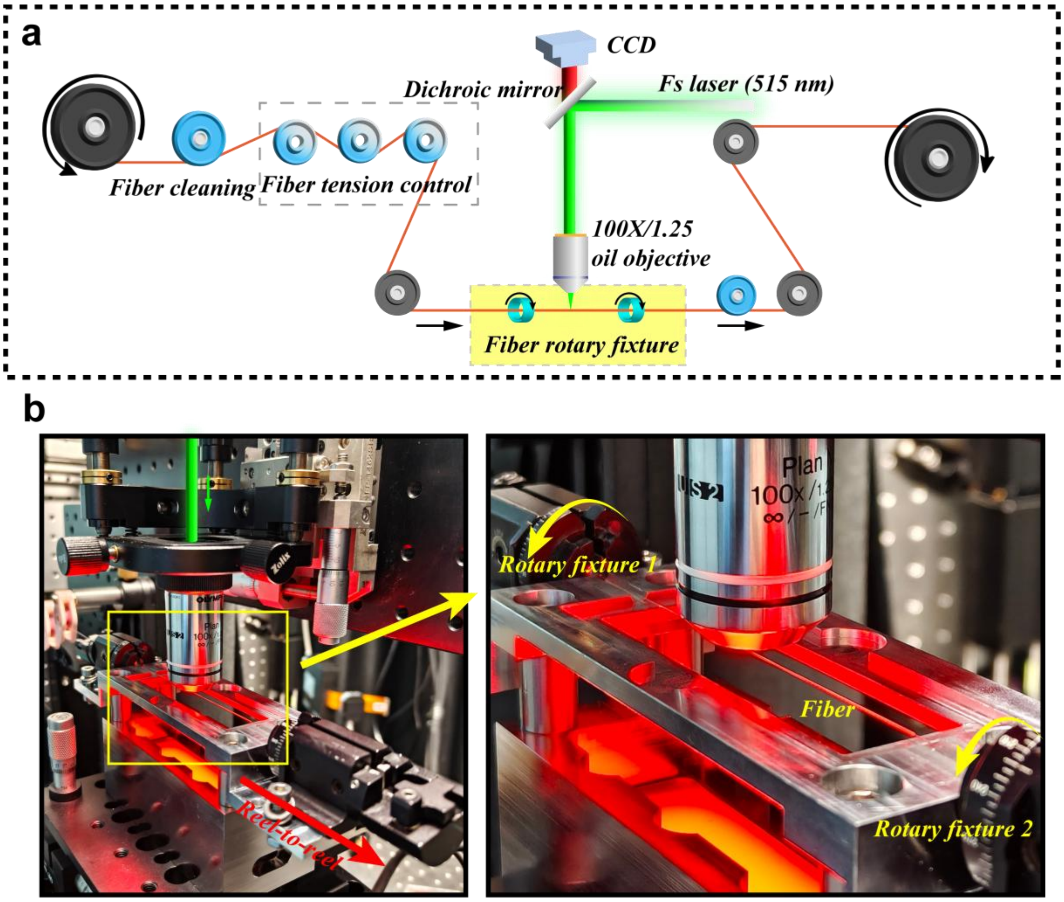

Figure S1: The reel-to-reel femtosecond laser direct writing system. a The schematic components of the system. b Photos of the inscribing part of the system.

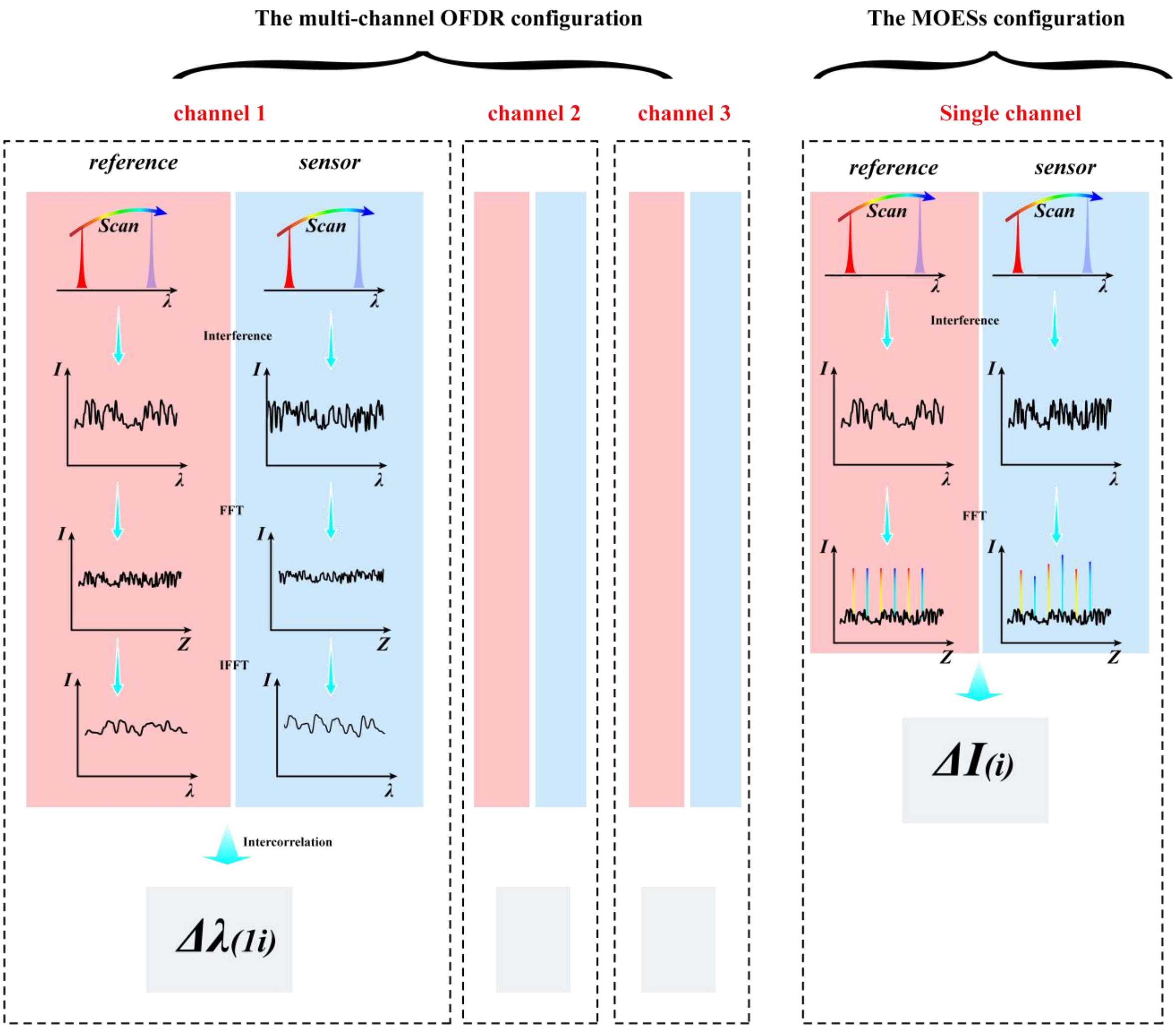

Figure S2: Comparison between multi-channel OFDR and MOESs fiber configuration.

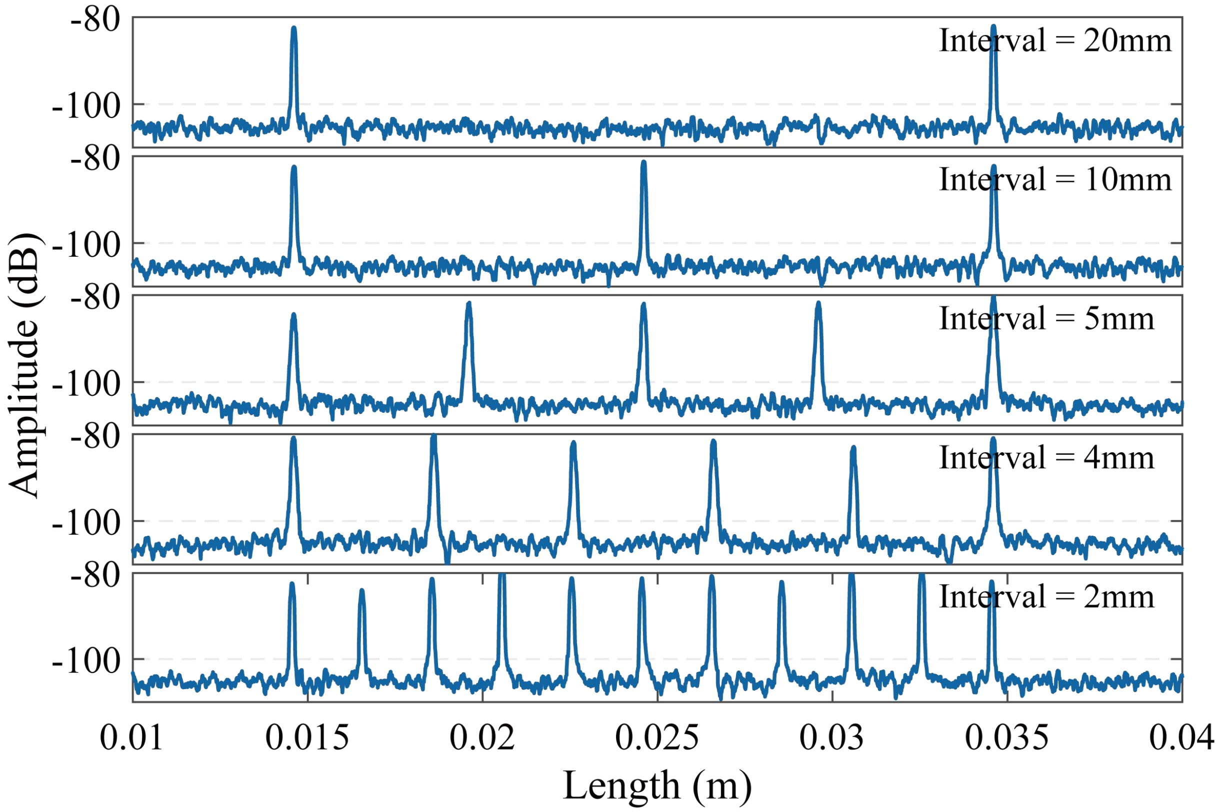

Figure S3: Backscattering profiles of scatterers fabricated with different misplacement distances, clearly distinguishing the position of scatterers with millimeter-length misplace, with an offset of 4 μm.

The spatial localization accuracy of the OFDR measurement was set to 100 μm, meaning the misplacement distance of the eccentric scatterers must exceed this value. Figure S3 shows the backscattering profiles of the eccentric scatterers array with misplacement distances of 2, 4, 5, 10, and 20 mm. Consequently, a misplacement distance of 2 mm for the eccentric scatterers array was sufficient to distinguish discrete scattering signals. The misplacement distance represents the spatial resolution of deformation encoding, which can reach the millimeter range.

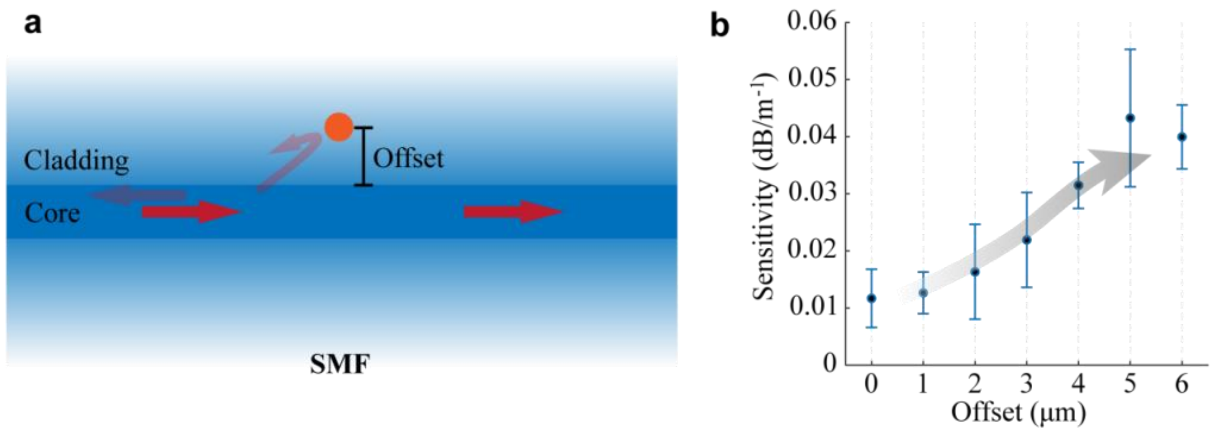

Figure S4: Relationship between scatterer offset and bending sensitivity. a Schematic illustration of eccentric scatterers inscribed at varying radial offsets from the core–cladding interface. b Measured bending sensitivity as a function of scatterer offset, showing an inverse Gaussian trend.

The peak intensity of backscattered light from an eccentric scatterer is related to its offset from the fiber core. In a single-mode fiber, the optical field follows a Gaussian distribution, resulting in weaker back-reflected signals from scatterers located closer to the edge of the mode field. In contrast, when the fiber is bent, scatterers with larger offsets exhibit stronger variations in backscattered intensity—that is, higher bending sensitivity. This behavior arises mainly from two factors: (i) scatterers with greater offsets experience higher stress during bending, enhancing scattering due to deformation and the photoelastic effect; and (ii) the relative intensity change at the mode field edge is more pronounced under bending.

To investigate this, we fabricated scatterers with varying offsets and measured their bending sensitivity, as shown in Figure S4. Taking the core–cladding interface as the zero-offset position, scatterers were inscribed outward with 1 μm steps. The resulting sensitivity profile (Figure S4 b) follows an inverse Gaussian trend.

Given the inverse relationship between peak scattering intensity and bending sensitivity, an offset of 4 μm was chosen in this work to balance signal clarity with bending responsiveness. The corresponding backscattered signals from the fabricated scatterer array are shown in Figure 2g of the manuscript.

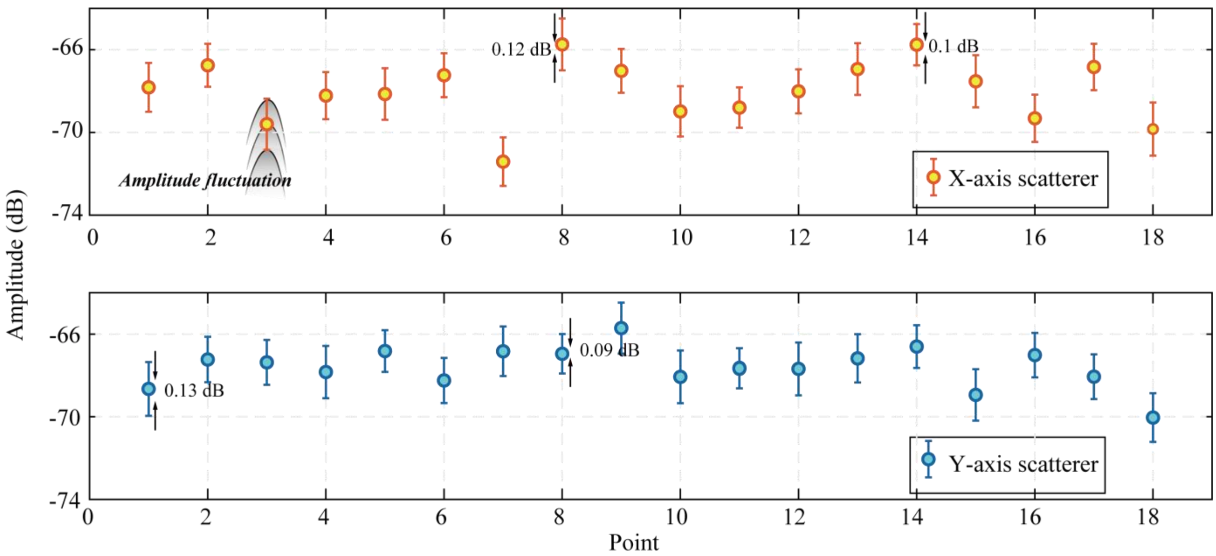

Figure S5: Fluctuations in scattering intensity measured along the X and Y-axis.

Although the signal peak intensity of each scatterer in Figure 3 exceeds 30 dB, the relatively low overall intensity (~-70 dB) poses challenges for signal measurement stability. To investigate the stability of intensity measurements, the sensing fiber with eccentric scatterers was fixed straight, and backscatter signals were recorded over 100 consecutive measurements. After peak detection and separation of X/Y-axis data, the standard deviation of intensity fluctuations was calculated, as shown in Figure S5. The minimum and maximum standard deviations of intensity fluctuations for scatterers along the X-axis were 0.1 dB and 0.12 dB, respectively, while for scatterers along the Y-axis, the range was between 0.09 dB and 0.13 dB. These intensity fluctuations lead to errors in curvature and angle calculations, thereby increasing the error in deformation encoding. To address this issue, random noise was reduced by averaging multiple measurements during signal processing, improving measurement accuracy to a certain extent.

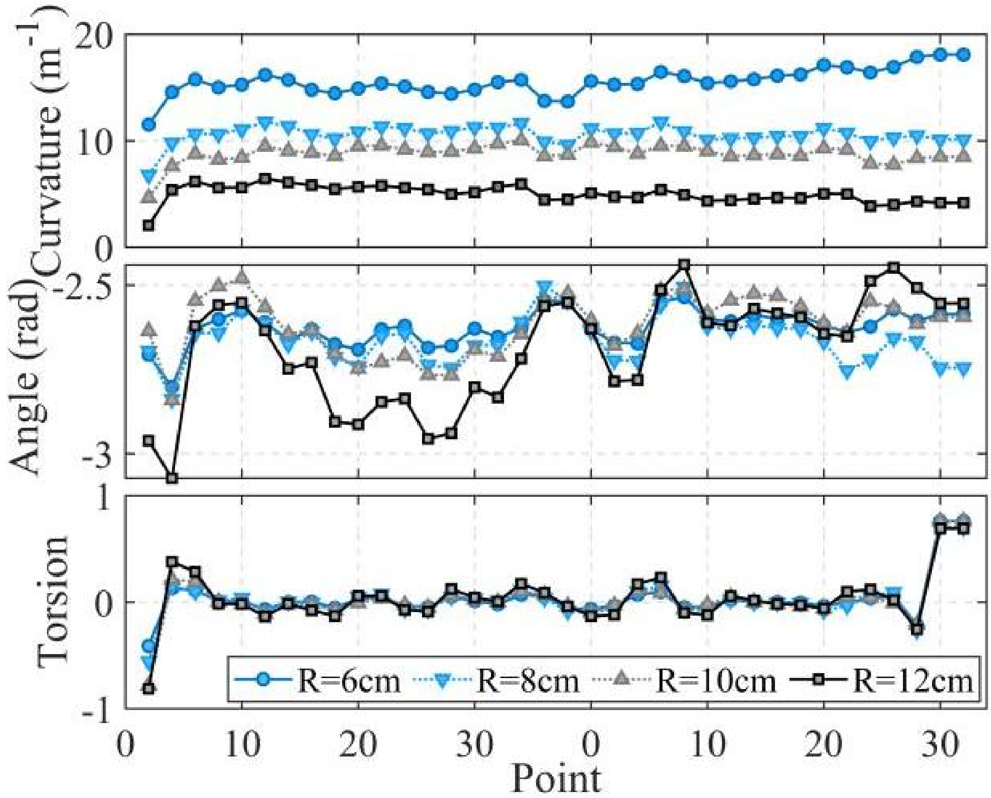

Figure S6: The angle, curvature, and torsion results of the circular arc curve with a bending radius of 6-12 cm.

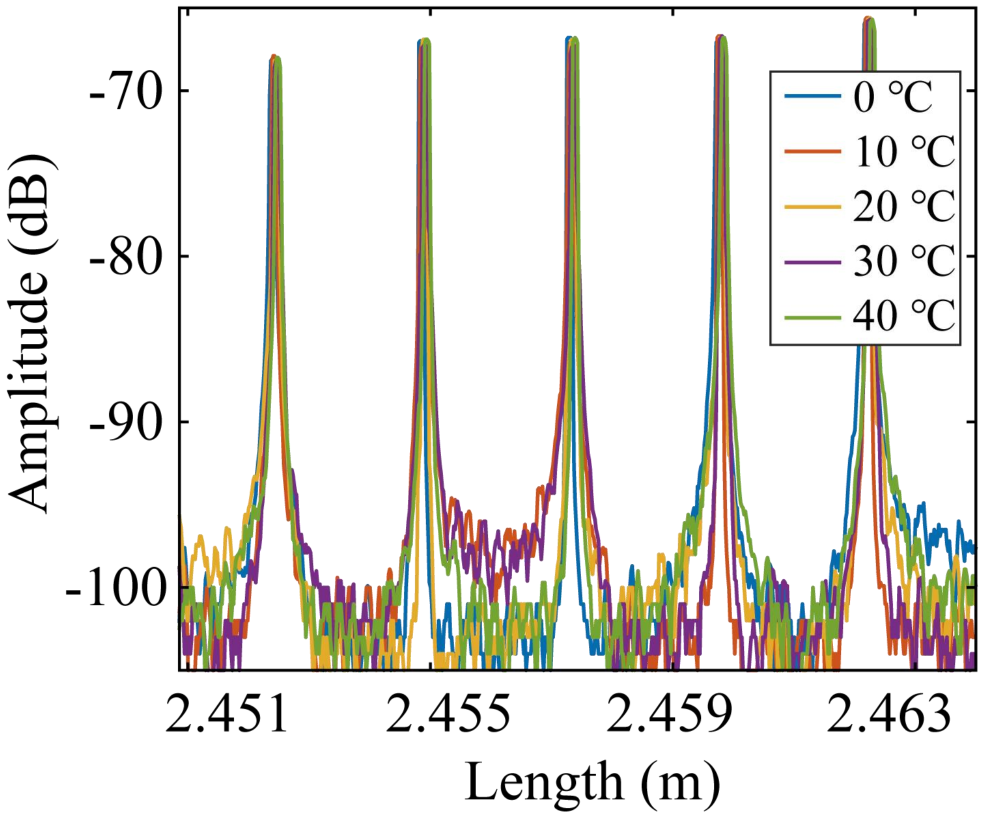

Figure S7: Variation in the backscattered signal profile with increasing fiber temperature.

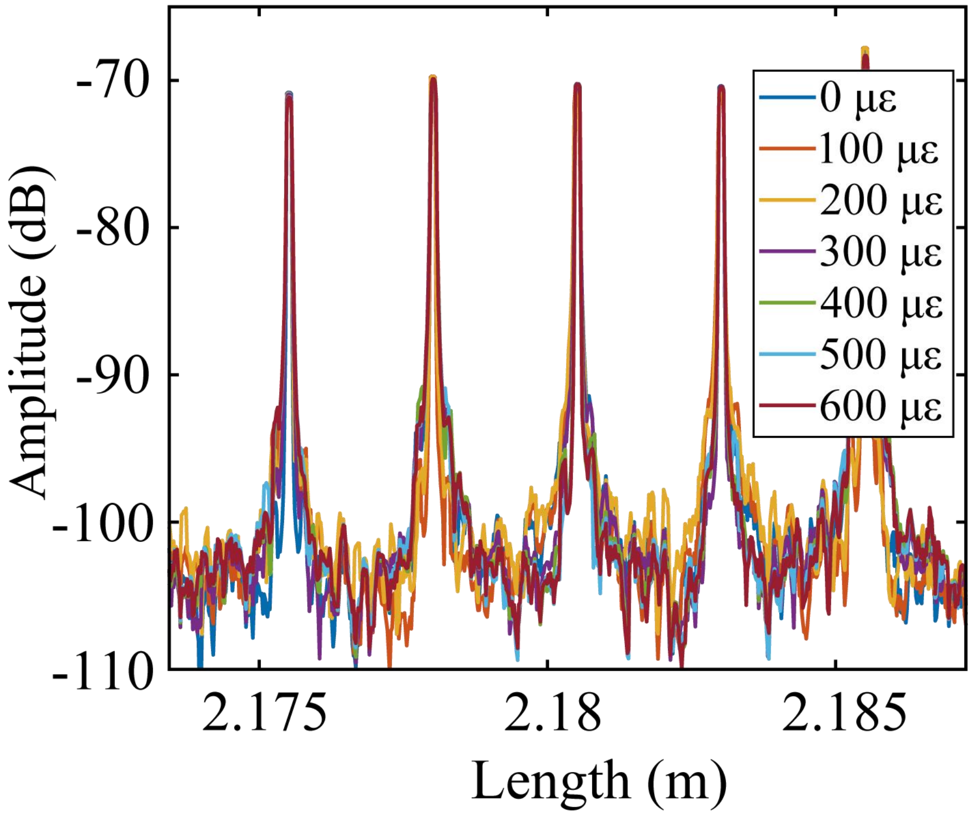

Figure S8: Changes in the backscattered signal profile as axial strain increases.

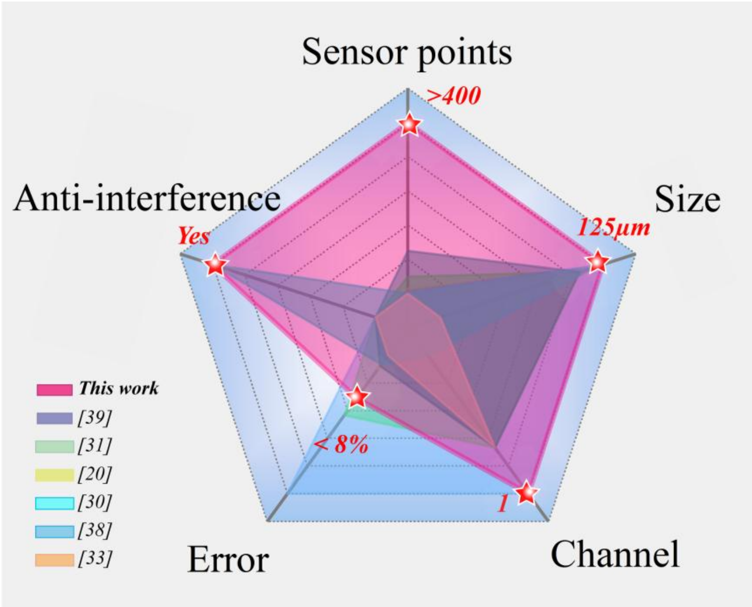

Figure S9: Comparison of deformation encoding performance between MOESs array fiber and other methods.