3D shape-sensor based on integrated optics in ultra-thin glass

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INTRODUCTION

3D shape-sensors based on (fiber-)optical methods for bend and curvature sensors often lack stability, reproducibility and application cases [1]. Using laser processing, Bragg gratings for curvature measurement can be integrated into ultra-thin glass in a precise manner. The monolithic character of the aluminosilicate glass ensures reproducible measurements as the neutral bending line (Figure 1a and 1b) is not moved when mounted on a surface. The EU-funded project “FleX-RAY” for novel, flexible X-ray detectors requires the use of a non-electrical shape-sensor to monitor the shape of the detector.

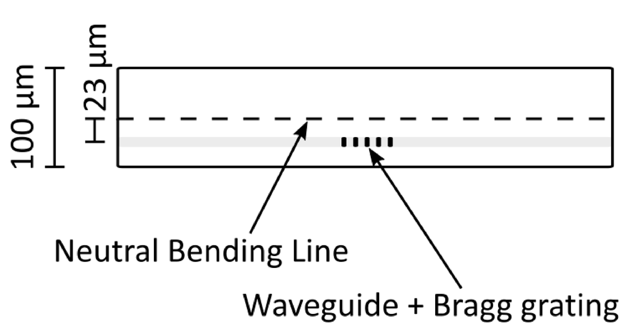

Fig. 1a Waveguide and Bragg grating parallel to neutral bending line

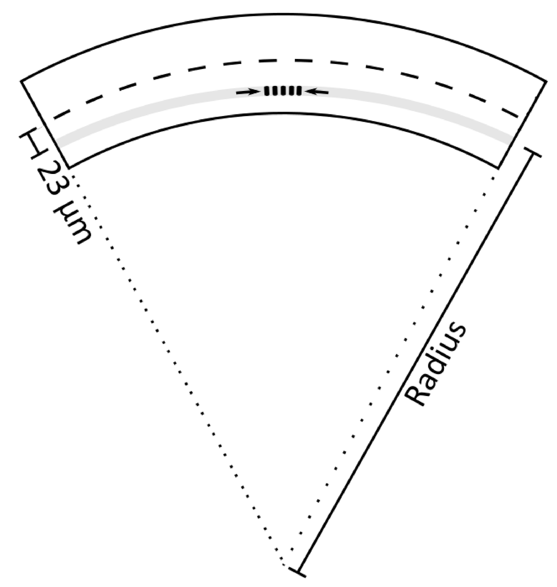

Fig. 1b Compression of Bragg grating under bending (positive curvature)

Ultra-thin glass offers mechanical stability, reproducible measurements, and the possibility of integrating Bragg gratings at definite points

METHODS

The dimensions of the ultra-thin glass are 50 × 50 × 0.1 mm³. Eight waveguides (four in x- and y-direction each) with four Bragg gratings (of 5 mm length) each placed equidistantly along the waveguides, were integrated into the ultra-thin glass 23 µm parallel to the neutral bending line (Figure 2a). For the processing of both the waveguides and the Bragg gratings, a femtosecond pulse laser with a one-scan technique employing a slit for beam shaping was used [2].

For sensitivity calibration, all 32 Bragg gratings underwent a five-point calibration on 3D-printed cylinders with curvatures ranging from 0 to ±20 m^{-1}. For linearity determination, the same curvatures were applied in a three-point bending setup.

Using a geometrical algorithm [3], the calculated curvatures of the Bragg gratings in one waveguide were inter- and extrapolated to a curve. The curves from all Bragg signals together form a 3D graph.

The wavelength shifts of femtosecond laser-processed Bragg gratings are recorded for different curvatures and a calibration function is calculated.

RESULTS

The spectrum (Figure 2b) of reflected Bragg signals shows four peaks corresponding to the four Bragg gratings within one waveguide. The intensity decreases with each next signal due to the attenuation of the waveguide (0.47 dB/cm).

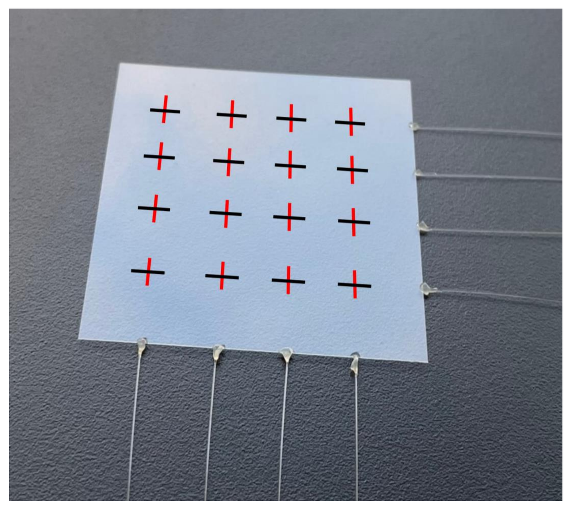

Fig. 2a 3D shape-sensor with eight feeding lines and four Bragg gratings each shown in black (x-dir.) and red (y-dir.)

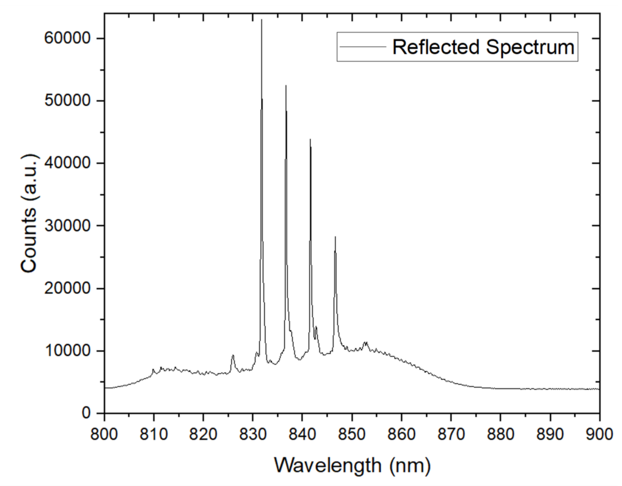

Fig. 2b Spectrum of reflected Bragg signals of one waveguide

The five-point calibrations show an average sensitivity of -17.8 pm/m^{-1}. But also a two-point calibration would be sufficient as the linear fit is highly linear at an average R-square of 0.995 (Figure 3).

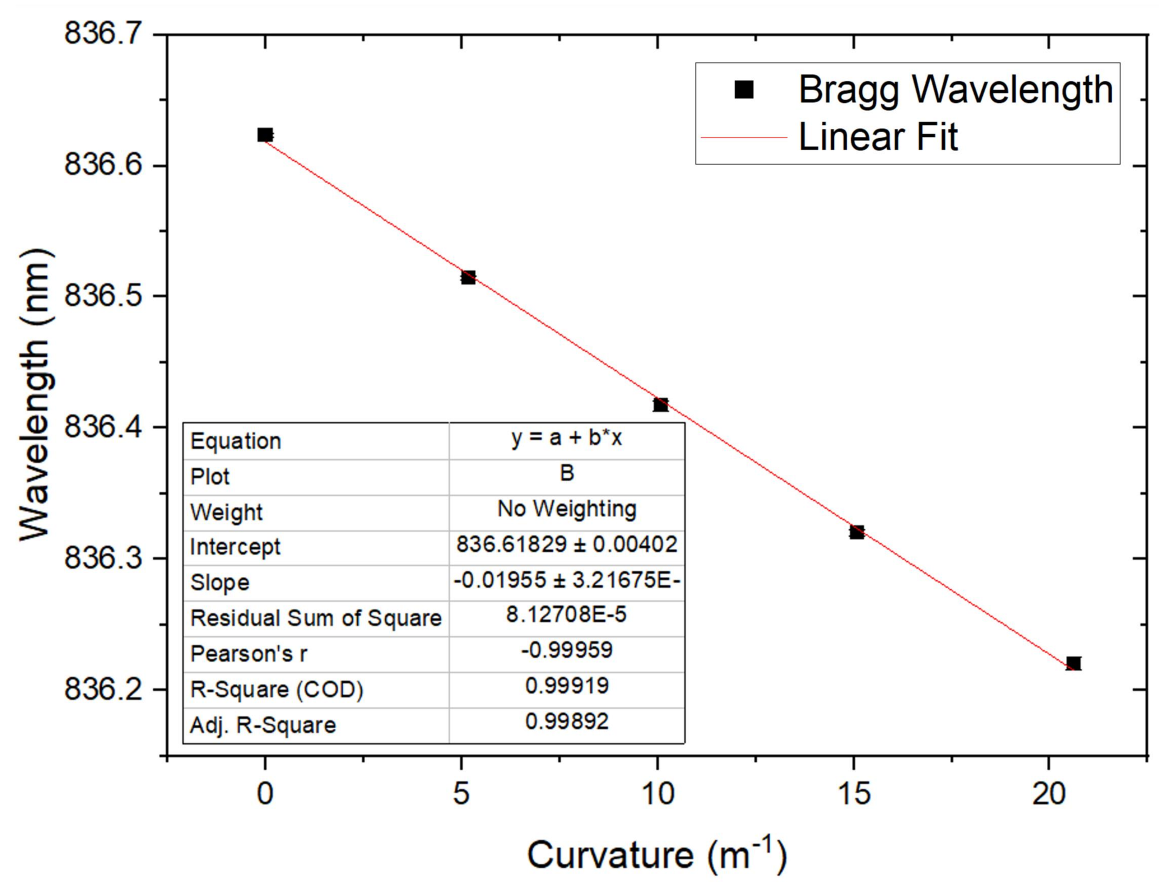

Fig. 3 Measurement for the determination of linearity of one Bragg grating with a linear fit. Error bars are smaller than the measurement symbols.

The average standard deviation for remounting the sensor is 2.6 pm, corresponding to an error of 0.15 m^{-1}.

For testing, the 3D shape-sensor was exposed to a curvature of 17.1 m^{-1}. Using the calibration functions, the curvature at each Bragg grating was calculated. When inter- and extrapolating the curvature data of each Bragg grating in a waveguide, the curve in Figure 4a is obtained. The error is 0.33 m^{-1} or below 2% as the last Bragg signal (Fig. 4a, at x=15–30 mm) is affected by the attenuation (Fig. 2b) for high curvatures. Repeating the process for all Bragg gratings gives the 3D graph in Figure 4b.

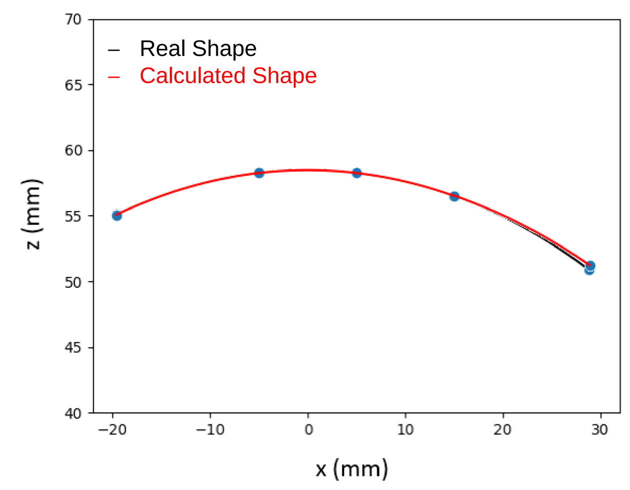

Fig. 4a Inter- and extrapolation of curvatures along one waveguide

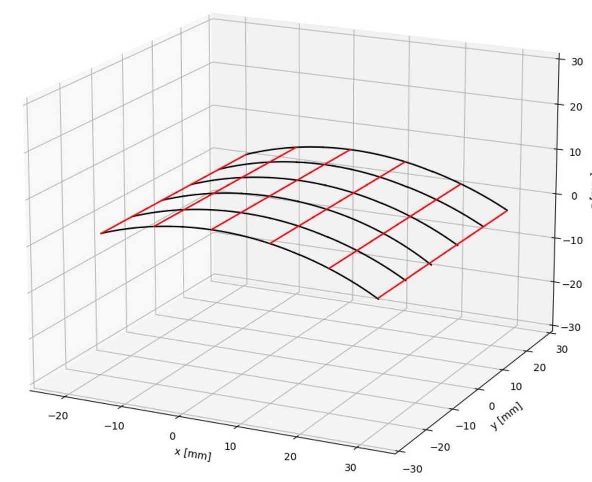

Fig. 4b 3D graph of calculated shape

The ultra-thin sensor needs to be calibrated only once and accurately reports the 3D shape.

CONCLUSIONS

1. **The signal response is highly linear.**
2. **Curvatures and the 3D shape are reported accurately.**
3. **No additional calibration is necessary after remounting the sensor.**

3D shape-sensors in ultra-thin glass deliver accurate and reproducible measurements with only a single calibration and are a good alternative to (fiber-)optical shape-sensors.

REFERENCES

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[2] Spence, D., Marshall, G., Ams, M., et. al., “Slit beam shaping method for femtosecond laser direct-write fabrication of symmetric waveguides in bulk glass,” Opt. Express 13(15), 5676-5681 (2005).
[3] Xu, L., Ge, J., Patel, J., et. al., “Dual-layer orthogonal fiber Bragg grating mesh based soft sensor for 3-dimensional shape sensing,” Opt. Express 25(20), 24727-24734 (2017).

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