A Simple Polymer-Optical Tilt and Displacement Sensor

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We present a design for a simple, full polymer-optical displacement sensor that is capable of detecting linear displacement (strain) as well as tilt between its two components. The simplicity of the device makes it compatible to many manufacturing processes, including hot-embossing, hot-roll lamination and assembly by hand.

1 Introduction

Strain sensors based entirely on optical effects have several benefits over the traditional electrical (resistive and piezoelectric) strain gauges. They are immune to strong magnetic or electric fields, can be used in hazardous environments and offer - depending on type - large multiplexing potential, which reduces cabling costs. The most prominent type of optical strain sensor is the fiber Bragg grating (FBG) sensor, where a periodical refractive index modification is written into a glass-optical fiber [1]. In the last years, these devices also found their way into the market. However, this type of sensor relies on expensive readout equipment and glass-optical fiber, making it unsuitable for, e.g., roll-to-roll or other high-throughput manufacturing processes. The displacement sensor presented here relies on a simple butt-coupling and a full-polymer approach and can be adapted to several manufacturing processes.

2 Working principle

The sensor consists of two arrays of waveguides, arranged opposite to each other across an elongation zone. With one array being the emitter and one array being the receiver side, light is coupled from the emitter to the receiver. If the elongation zone is compressed or elongated, the gauge length l between emitter and receiver changes and an increase or decrease of coupled intensity can be monitored, respectively, see Figure 1.

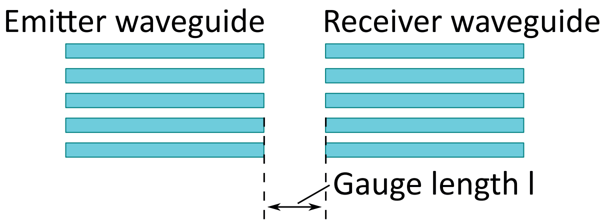

Figure 1 *Working principle of the displacement sensor.*

The sensitivity of the proposed sensor is mainly dependent on the structure sizes of the used waveguides as well as on the gauge length. Since different production processes enable different structure sizes, the resulting sensitivity is mainly depending on the manufacturing process. Figure 2 shows the sensitivity for three different designs, based on commercially available $1\mathrm{mm}$-diameter plastic optical fiber (POF), laminated waveguides with $100\mathrm{\mu m}$-diameter and hot embossed waveguides with a $25\mathrm{\mu m} \times 25\mathrm{\mu m}$ cross section, respectively. The calculations are based on a gauge length of $l = 100\mathrm{\mu m}$ and a strain ranging from $\epsilon = -0.5\%$ (compression) to $\epsilon = +0.5\%$ (strain). The sensitivity is calculated as the gradient of the coupled power I over gauge length, $\mathrm{d}I/\mathrm{d}\epsilon$.

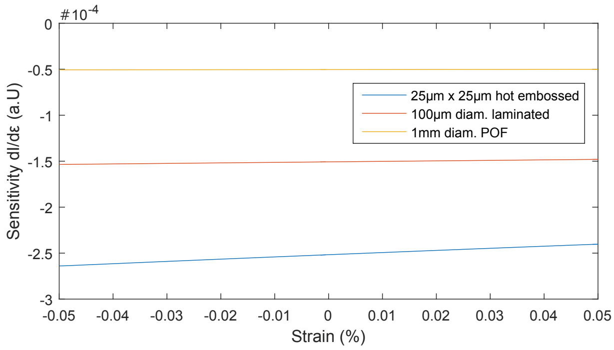

Figure 2 *Sensitivities for three different production methods of the proposed strain sensor. All sensors where calculated with a gauge length of* $l = 100\mathrm{\mu m}$.

It can be observed that the sensitivity increases with decreasing structure size when the gauge length is held constant. Therefore, sensors with large-sized structures are more suitable for measurement of large structural changes (e.g., as a crack monitoring device in buildings [2]) while small-sized sensors can be applied for strain sensing applications in a similar fashion as electric strain gauges.

3 Experimental setup and performance

For the characterization of the sensor, we built a device using ESKA CK-10 POF, adhesively bonded to a polymethylmethacrylate (PMMA) substrate. Five bare fibers where fixed axially parallel to each other and, after curing of the adhesive, the substrate was cut in two halves, one acting as the emitter and one as the receiver side.

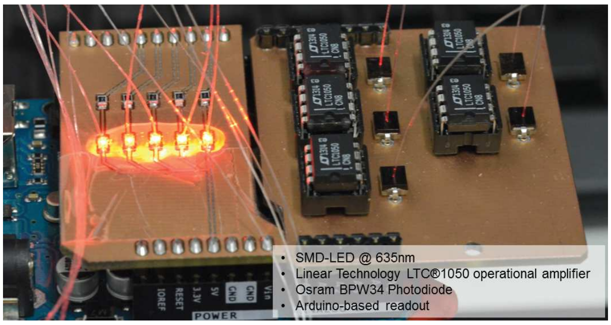

Figure 3 *Photograph of the readout electronics consisting of incoherent SMD-LEDs and a photodiode amplifier circuit.*

The fibers to the emitter where connected to SMD-LEDs controlled by an Arduino microprocessor while the POF coming from the receiver were connected to Osram BPW34 photodiodes and read out using the same device (Figure 3). Both the emitter part and the receiver part of the sensor where fixed on a stage for measurement with a free space gap (simulating the gauge length) of $100\mu m$ between them, Figure 4.

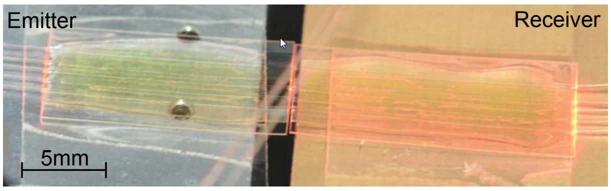

Figure 4 *Photograph of sensor prototype on the measurement setup.*

3.1 Displacement measurements

We carried out displacement measurements with the sensor starting at a gauge length of $l = 100\mu m$, the results are shown in Figure 5.

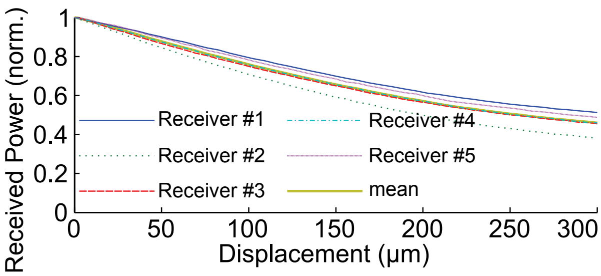

Figure 5 *Received power over displacement measured with the sensor system shown in Figure 3.*

The progress of received power (normalized to the initial power) over displacement is the same for all five emitter-receiver pairs within errors, as indicated by the average value which is also displayed. The slight differences between each receiver can be accounted to different qualities of the waveguide facets where, e.g., scratches lead to a wider beam angle and, therefore, to a steeper curve. With the simultaneous readout of all five emitter-detector pairs it is possible to compensate such errors which leads to increased accuracy without the need for calibration of the device.

3.2 Tilt measurements

Tilt measurements were carried out by tilting the receiver array of the sensor from 0 to 0.04rad with respect to the emitter array.

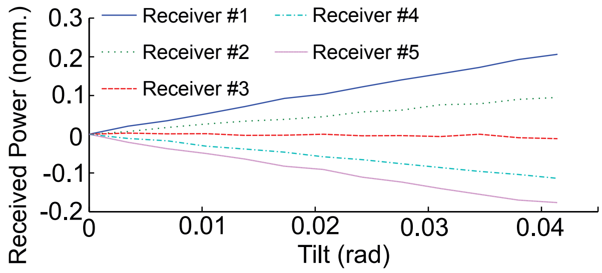

Figure 6 *Received power over tilt angle measured with the sensor system shown in Figure 3.*

The results in Figure 6 show the difference in coupled power of each receiver to the average value, starting at 0 for a tilt angle of 0. It is obvious, that the coupled power of the individual receivers are increasingly differing compared to the mean value, indicating an increasing tilt angle.

4 Conclusion

We presented a concept for a combined displacement and tilt sensor which can be implemented using different techniques ranging from assembly by hand to lamination or hot-embossing. The proposed design sensitivity is mainly depending on the structural size that is typical for the chosen production process. The prototype of the proposed device shows a clear difference in behaviour for displacement or tilt, thus, making both distinguishable from each other.

References

[1] C. K. Leung, K. T. Wan, D. Inaudi, X. Bao, W. Habel, Z. Zhou, J. Ou, M. Ghandehari, H. C. Wu, and M. Imai, "Review: optical fiber sensors for civil engineering applications," Materials and Structures **48**(4), 871–906 (2015).

[2] M. Rahlves, C. Kelb, E. Reithmeier, and B. Roth, "Methodology for the design, production, and test of plastic optical displacement sensors," Advanced Optical Technologies (2016).