COMPACT GAS-FLOW SENSOR BASED ON ELASTOMERIC TRANSPARENT MICROWIRES
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ABSTRACT
We demonstrate a new opto-mechanical gas-flow sensing scheme utilizing transparent elastomer microwire as the transducer. Our lost-wax casting-based fabrication technique produces microwires strongly anchored at both of their ends to supporting structures, which allows substantial stretching of the microwires and detection of gas-flow with simple optical intensity measurement [1]. The elastic nature of the microwire also enables mechanical tuning of the sensing range. Using a compact setup, we measured flow velocity up to 5.1 m/s.

KEYWORDS: Optical microwire, Flow sensor, PDMS

INTRODUCTION
The demands for robust and wide-range gas-flow sensors have been strong for healthcare, structural, and environmental monitoring applications. The flow-induced bending of optical fibers has been frequently utilized for this purpose owing to their electromagnetic interference (EMI)-immune and spark-free nature. The use of conventional glass optical fibers for gas-flow sensing, however, incurs problems associated with the inherent rigidity of the glass material, such as the need for making the fiber thinner through wet-etching and the high probability of the thinned fiber breaking during their operations. Conventional polymer optical fibers are more flexible than the glass fibers but still not soft enough to yield sufficient bending in response to weak gas-flow [2,3]. We recently demonstrated a new technique (shown in Fig. 1) to fabricate elastomeric transparent microwires that are very soft and capable of withstanding a high degree of stretching [1].

Since our technique practically grows the microwires from one supporting structure into another, the completed microwires are anchored to PDMS slabs monolithically and orthogonally. When straightened, the microwire works as an efficient lightpipe. Figures 2a-d show the stretchable and optically transparent characteristics of the microwire. The PDMS wire can withhold multiple cycles of >400% elongation and >70 mN of pulling force without sacrificing their optical functionalities [1]. In this work, we report a simple yet efficient gas-flow sensor using the PDMS microwire as the transducer.

Figure 1: The process flow for the lost-wax casting fabrication of PDMS wires (a-b) the first replication of metal wire to wax transition mold (c-e) the second replication to PDMS wires [1]

Figure 2: Microscopic image of a 170 µm-diameter, 2.5 mm-long microwire (a) before (b) during 440% elongation (c) magnification at the anchoring site (d) a 180 µm-diameter microwire used as an optical jump-wire [1]
THEORY

For optical gas-flow sensing, interferometric or spectroscopic interrogation schemes have been mainly utilized but they are generally bulky and complex [4,5]. Instead, we adopted the simple, optical intensity interrogation in this work. Figure 3 shows the basic setup of our gas-flow sensor schematically. The elastomeric optical microwire bends in response to the gas-flow. By utilizing the microwire itself as a lightpipe, we could directly translate the degree of bending into changes in the optical throughput. When gas flow is introduced at the center of the microwire, the fluid drag force

\[ F_D = \frac{1}{2} \rho AU^2 C_D \]  

induces bending of the microwire (\( \rho \): fluid density, \( U \): flow velocity, \( C_D \): drag coefficient, \( A \): the cross-sectional area of the microwire exposed to the flow) [6]. Bending of the microwire shifts the center of the output beam. By placing a pinhole in front of the detector, we can translate the center-to-center displacement between the output beam and the pinhole into a decrease of the optical throughput. By comparing the output intensities of the unperturbed and perturbed setups, we can estimate the flow velocity. In addition, the degree of bending under a certain level of flow velocity can be modified by adjusting the tension of the microwire. Since a simple stretching increases the tension of the microwire, we could tune the range of gas-flow sensing mechanically.

EXPERIMENTAL

Using the setup shown in Fig. 3, we measured the optical throughput as a function of the gas-flow velocity. As the transducer, we used a 9 mm-long, 188 \( \mu \)m-thick PDMS microwire attached between 1.5 mm-thick PDMS slabs. A 630 nm HeNe laser with 290 \( \mu \)W output power was used as the light source. For in- and out-coupling of the light, two 10x objective lens were used at both input and output ends of the optical microwire. The input end of the PDMS slab was fixed while the output end was attached to a linear translation stage to control the elongation. Also, a 1 mm-diameter pinhole was placed in front of the optical power meter.

![Figure 3: Experimental setup for PDMS optical microwire based gas flow meter: Under the gas flow, the bending of the optical microwire reduces the optical throughput in the presence of a pinhole](image)

Once the PDMS microwire was aligned and straightened, its output power was measured for the ambient flow. As a gas-flow source, we used compressed dry air (CDA) regulated at 25 psi. The amount of the applied flow rate was controlled between 0 to 5 SLM with a mass flow controller (Omega FMA5518). The tubing connected to the output of the mass controller was positioned 9 mm above the center of the optical microwire. Optical power meter (Newport 2931C) was set to generate the average value after sampling 120 seconds at 1 kHz. Then, the optical throughputs was recoded as a function of the gas-flow rate. The length of the optical microwire was also changed to adjust its tension.

RESULTS AND DISCUSSION

Figure 4 shows the optical throughput as a function of the gas-flow rate for two different levels of the microwire elongation. The symbols represent the measured data, and the lines show their polynomial interpolation for visual aid. The circles denote the data of the initially straightened microwire. Because even a slight bending of the microwire can reduce the throughput significantly, we set the initial length by finding an abrupt change in the throughput as the microwire was gradually straightened. The sensitivity obtained from this initial length was 5.5dB/SLM. After elongating the microwire by 200 \( \mu \)m from the initial length, the measurement was repeated. The results are shown as triangles in Fig. 4. As shown in the graph,
elongation produces a higher degree of tension and makes the microwire withstand a higher gas-flow rate. The higher tension not only expands the sensing range of the microwire but also shifts the center portions of the curve from 1.5~3.0 SLM to 2.0~4.0 SLM.

![Figure 4: The measured values of optical throughput as a function of applied gas flow rate](image)

**CONCLUSION**

In this work, we report the realization of a gas-flow sensor utilizing PDMS microwires, fabricated by lost-wax casting, as the transducer. The elasticity of the structure allows the use of simple optical intensity measurement-based interrogation and mechanical tuning of the sensing range. The sensitivity of the initially straightened microwire and 200 µm-elongated microwires are 5.5dB/SLM and 2.8dB/SLM, respectively. This type of all-optical tunable transduction mechanism will facilitate flow rate measurement of active gases in which the use of electrical sensors can be unsafe.

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**REFERENCES**


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