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Absolute length sensor based on time of flight in stretchable optical fibers

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Abstract—Soft and stretchable optical fibers are a promising all-polymer sensor element for extreme mechanical strains, pressures, bending and other deformations. Compared to electronic sensors, the sensor elements are intrinsically stretchable and are not subject to electromagnetic interference. However, the typical approach of measuring deformation by tracking the transmitted light intensity is an integrating approach similar to resistance-based measurements; it does not provide information about the location or the nature of the deformation. This paper describes an alternate method for driving stretchable optical fibers, a consumer LIDAR (LIght Detection And Ranging) chip connected to both ends of the fiber to measure its length via the time of flight (TOF) of a light pulse. This approach is a miniaturized, optics-based version of previous acoustic TOF and electronic time-domain reflectometry in robotics and human-interface devices. Such ranging systems collect spatial information using a small number of sensors. We found that the TOF approach can measure fiber lengths to within 1 mm on an overall length of ~330 mm (>1% accuracy). Both the amplitude and TOF methods were sensitive to pressures that created microbending, but in opposite directions. For bending radii greater than 7.5 mm, the TOF sensor was less sensitive to bending than the amplitude-based sensor. As a result, the TOF sensor accurately measured the perimeter of a shape with small-radius corners, while the amplitude-based sensor overreported the perimeter because of bending losses. Compared to earlier work, the TOF devices were less dependent on manufacturing variations that affected the signal level, such as fiber-source and fiber-detector alignment. We conclude that the amplitude method may be preferable for pure bending sensors, TOF sensors can distinguish pressure from stretching, and the TOF approach is notably better at measuring lengths over topography, such as in clothing-sizing and other wearable applications.

Index Terms—Integrated optics/fiber optical devices, time-of-flight, stretchable optical fibers, strain sensor, waveguide

I. INTRODUCTION

Optical sensors made from elastomers can bring mechanical deformation sensitivity to all-polymer wearable devices and soft robotic structures. In this paper, we apply a miniaturized time-of-flight optical sensor to make absolute length measurements on stretchable optical fibers developed in previous work [1]. Earlier research on stretchable optical fiber systems from our group and others was limited to sensing the amplitude, rather than the travel time, of the transmitted light. The limitation with that approach is that amplitude measurements are sensitive to other signals such as bending and any deformations that misalign the light source and detector. While we desire to measure these signals in some applications, often we only want length and must apply additional sensors to subtract out the interfering signals.

Because stretchable optical fibers are relatively shorter than conventional silica optical fibers (10-100 cm rather than several km thanks to the lack of highly transmissive stretchable materials), and the speed of light is high, travel times are extremely fast, on the order of nanoseconds. To measure sub-nanosecond travel times required for millimeter-scale spatial resolution would conventionally require an optical bench interferometer or fast photodetector plus expensive ($40-50k) high bandwidth signal analyzer. Only in the past five years have low cost chips for LIDAR (LIght Detection And Ranging) become available for measuring optical time-of-flight over short, 3 – 400 cm path lengths. These chips, designed as mobile phone peripherals that detect the distances to users' hands and faces without errors caused by different surface reflectivities, are meant to transmit and receive infrared light signals in free space, not in waveguides. In this work, we made fixtures to connect stretchable optical fiber waveguides to the source and detector of the VL53L0X sensor (ST Microelectronics) as shown in Fig. 1. Its onboard 940 nm wavelength laser light source is a good match to the transmission range of our fibers' urethane core. No focusing optics were used, keeping the intensity at or below the safe level emitted by the chip.

II. BACKGROUND

Time-of-flight (TOF) optical sensing has previously been used to characterize non-stretchable optical fiber assemblies [2]. While time-domain measurements in optical fibers can be used for position sensing and shape sensing, frequency-domain reflectometry is more common [3].

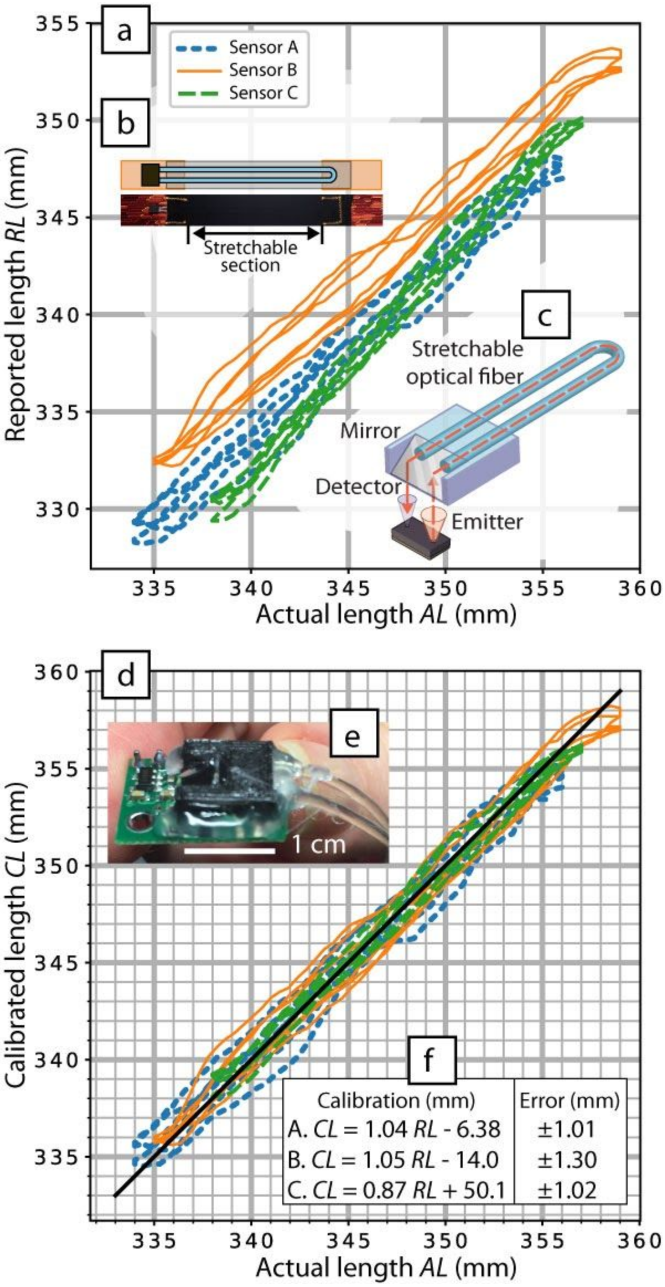

Fig. 1 a.) Data from three fabric-embedded stretchable optical fiber TOF sensors; three cycles plotted vs the known length after a 10-point moving average was performed on the as-received length data. b) Inextensible fabric tabs define the stretchable section and prevent mechanical strain from being transmitted to the chip housing. c) Schematic showing the fiber, the sensor chip (VL53L0X, ST Microelectronics), and a mirrored housing that converts the chip into a side-looking device. d) Calibrated data lines up with the known length. e) Photo of chip-housing-fiber region for comparison with illustration. f) Calibration formulas used to align the three data sets with the known length values, with coefficients obtained by linear least squares fitting. The error is obtained as the standard deviation of *CL-AL* (Calibrated Length – Actual Length) over all data points for each sensor.

Optical reflections are also measured from translucent biological tissue to reconstruct 3D images at the microscale using optical coherence tomography [4], a technique likened to ultrasound with light in place of sound waves.

Because many organic materials have intrinsic stretchability, researchers have turned their attention to polymeric optical fibers and other soft optical materials as reviewed in 2019 [5,6]. Stretchable optical sensor materials include extruded thermoplastic elastomers [1,7], molded hydrogels [8], cast silicones [9,10], and 3D printed ballistic gel [11]. Soft optical strain sensing is a relatively new field. In comparison, electronic resistive and capacitive sensors dominate both research efforts and commercial products for sensing extreme deformations (20-30% or greater length change). Recent efforts include printed Pickering emulsions [12] and liquid metal-filled channels [13], used as stretchable length, bending and pressure sensors. Such work is typically directed at capturing motion in human-wearable sensors that interface with robots [14,15], as well as in soft robots themselves. However, since the end-to-end electrical signal is an integrated single measurement, and so is the end-to-end optical transmission amplitude, all of the resulting amplitude-based sensors have similar problems: stretching and diameter reduction combine to modulate the output signal in a way that cannot be resolved without knowing the nature of the deformation.

Time-of-flight in guided channels has previously been applied in *acoustic* measurements to detect the length of pipes [16], and much more recently, to detect the shape of soft robotic fingers [17] and the locations of pressures applied to soft tubes for human-computer interfaces [18]. Although this method uses sound waves instead of light, it is analogous to our time-of-flight optical measurements in that the travel time of an applied signal is correlated with the spatial arrangement of the transmission volume in order to gather information about the shape. For *electronic* signals, researchers have shown that time-domain reflectometry, a method commonly used to pinpoint the location of defects in transmission lines, can determine where users touch wires, including guitar strings and conductive paths on soft stretchable surfaces [19] using a single electrical connection point. Based on their findings, the authors suggested a similar time-of-flight approach for optics-based user interfaces. Consumer LIDAR chips now make it possible to package optical TOF in a portable system.

III. METHODS

A. Fabrication

Stretchable multimode optical fibers with a urethane core (index of refraction n=1.53 and diameter 1mm) and a silicone cladding (n=1.41, 0.2 mm thickness) were produced as described in [1], then sandwiched between two pieces of elastic fabric (86% Nylon/16% Elastane, Harmony Black from Eclipse Textiles). The layers were bonded together at 260 °C using a heat-bondable stretchable film (3415 Sewfree Adhesive Tape, Bemis Associates, Inc). Fig. 1b shows the packaged sensor with inextensible fabric pull tabs for cyclic stretching. A 3D printed block held the fiber up to a 5x5 mm mirror oriented to couple the fiber ends to the ports of the LIDAR chip, providing a closed path for the optical signal; we used a breakout board (Product 2490, Pololu Robotics and Electronics, Fig. 1e) and its code library to record length readings on a microcontroller. For comparison, amplitude sensing was performed with a VEML7700 ambient light sensor (Vishay, Inc). Fiber lengths from sensor to "u-turn" (Fig. 1b) were in the 320- 330 mm range.

B. Testing

Four tests were performed on the TOF sensors: cyclic stretching (Fig. 1) on a stepper-motor controlled track, bending, local pressure, and a looped circumference measurement. The same tests were conducted on amplitude based sensors, except for cyclic stretching results which are available in [1]. *Local pressure* tests (Fig. 2) were carried out by placing weights on a force-concentrating structure: three pencils (7.3-7.5 mm diameter), resting across two sensors. *Bending* tests (Fig. 3) were performed by wrapping the fabric-embedded sensors around cylinders of different diameters without stretching. Finally, *looped circumference measurements* were done by stitching the sensors into 200-mm circumference stretchable loops (Fig. 4 inset). Plastic cylinders were purchased and fabricated, including a 3D printed rounded square having a 1 cm corner radius and 228 mm perimeter designed to equal the perimeter of one of the cylinders. Amplitude and TOF sensors were stretched over each cylinder at least three times, at least 20 sensor readings were collected each time and the sensors were calibrated by fitting a line through the sensor signals *vs.* known cylinder circumferences. Then, the cylinder-based calibration was applied to the signal from the square shape, translating it into a length in millimeters.

IV. RESULTS

Cyclic stretching tests in Fig. 1 were conducted on three samples to find a calibration routine that could align different sensors' data to the known length. Fig. 1a shows three cycles of as-received data smoothed by a 10-point moving average, while Fig. 1d is the calibrated length (*CL*) result from running each smoothed received-length (*RL*) data point through a calibration ($CL = A \times RL + B$) where the coefficients *A* and *B* were obtained by fitting a line through the data in Figure 1a. The linear calibration led to sensor errors (standard deviation of *RL-AL*, where *AL* is actual length) in the 1mm range on overall lengths in the 330-360 mm range; errors are listed in Fig. 1f. Compared to amplitude-based sensors, which have an exponentially decaying intensity-*vs.*-length relationship characterized by the *ratio* of transmission between the stretched and unstretched fiber, the TOF sensors are linear and absolute. Because transmitted intensity depends on source alignment, amplitude values were highly sensitive to manufacturing variations, while the three uncalibrated TOF length sensors' data (Fig. 1a) nearly overlapped.

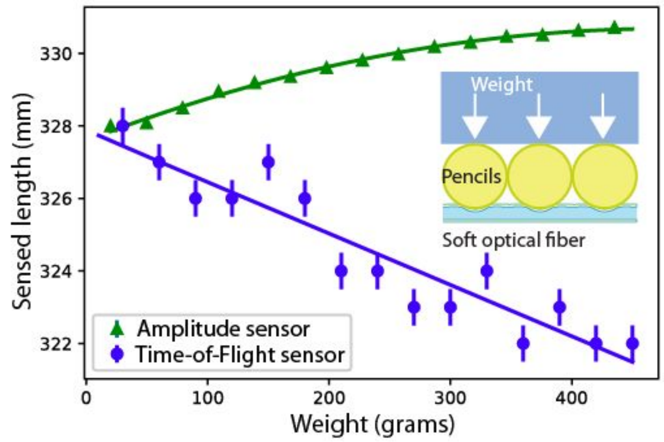

Fig. 2. Effect of pressure on time-of-flight and amplitude sensors, with 2nd order (amplitude) and 1st order (TOF) polynomial data fits.

Local pressure tests (Fig. 2) showed that pressure *increased* the length reported by the amplitude sensor, because distortions at the interface caused light to scatter out of the fiber for a lower intensity at the detector. Meanwhile, the TOF sensor's reported length *decreased,* likely because microbending preferentially attenuates higher-order, slower-traveling modes, shifting the peak of the detected light toward shorter arrival times. The maximum 450 g weight, divided by the approximate contact area of the pencils to the fibers, translates to the 10 to 20 Pa range, or the typical contact pressure of a human foot supporting body weight. In length sensor applications, both types of sensors should be protected from concentrated pressures like those in Fig. 2. The opposite-sign responses of the TOF sensor in Fig. 1 *vs.* Fig. 2 also suggest that it can distinguish pure pressure from pure stretching.

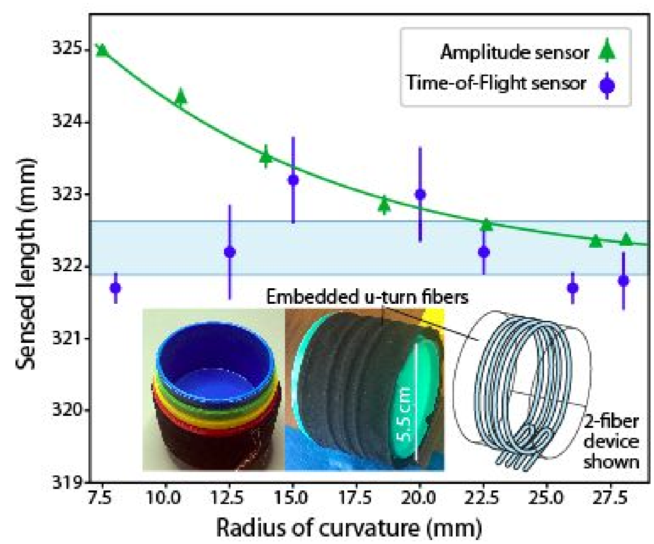

Fig. 3. Time-of-flight and amplitude sensors were wrapped over cylinders without stretching (inset). The horizontal band on the plot is a 95% confidence interval based on all reported length samples from the time-of-flight sensor, while the amplitude sensor curve is a fit to an optical fiber bending loss model [20].

In Fig. 3, the amplitude sensors are shown to respond to bending radius while the TOF sensors show a random response down to the smallest radius tested (7.5 mm).

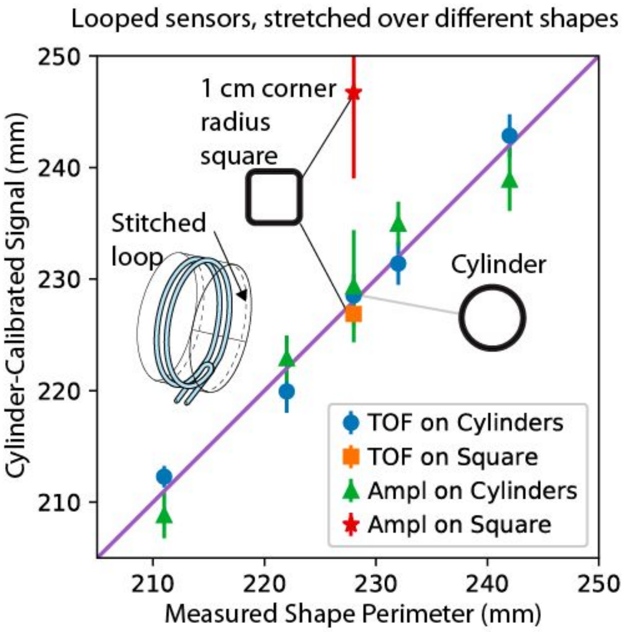

Fig. 4. Time-of-Flight ("TOF") and Amplitude ("Ampl") sensors were formed into 200 mm circumference loops and stretched over cylinders and a square form (insets), producing an 8% overestimate of the square perimeter from the amplitude-based sensor.

Fig. 4 shows that bending losses caused the amplitude sensor to overreport the shape perimeter compared to the time-of-flight sensor, which reported the same perimeter as the equivalent cylinder within experimental error. Different rotations of the square were also observed to cause the sensor to run across corners either 4 or 5 times because of a 1 cm overlap at the sensor end, increasing the uncertainty in the amplitude sensor reading on the square when compared to the other measurements.

V. CONCLUSION

The TOF approach to measuring signals from soft optical fibers has advantages over amplitude-based methods when 1) sensors are sought to measure path lengths over variable topography, such as a sensorized test garment for clothing sizing, and 2) where manufacturing variations are expected to create small errors in fiber-detector and fiber-source alignment. Where a bending sensor is needed, the amplitude-based sensor is a better match. Both types of sensors should be isolated from pressure-driven microbending that scatters light into the cladding and surroundings, however, the TOF sensor's bidirectional response makes it capable of sorting stretching from controlled pressure. A chip that combines TOF and amplitude sensing modes on a single fiber could potentially capture combinations of path length, pressure and bending with a single, all-polymer stretchable sensor element.

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