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A Flexible Dual-Core Optical Waveguide Sensor for Simultaneous and Continuous Measurement of Contact Force and Position

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***Abstract*— Having the merits of chemical inertness and immunity to electromagnetic interference, light weight, small size, and softness, optical waveguides have attracted much attention in making tactile sensors recently. This paper presents a new design of waveguide using two layers of cores, one of which has an uniform width and the other has an incremental width. It is deduced and verified that the contact force can be derived from the light power loss in the uniform-width core, while the contact position can be derived from the light power loss in the other core together with the estimated force. By this dual-core design, a single waveguide can simultaneously and continuously measure the contact force and position along it, which makes it very suited for integration on some thin long robotic parts, such as robotic fingers. A hardware experiment has been conducted to demonstrate its effectiveness on a two-finger gripper in an assembly task. The dual-core waveguide achieves 2 mm spatial resolution and 0.1 N sensitivity.**

I. Introduction

Tactile sensors are essential in extending robot's functionality and applicability to the case where precise grasping and manipulation capabilities are required. Various principles have been used to develop tactile sensors, such as piezoresistive sensor [1], capacitive sensor [2], piezoeletric sensor [3], quantum tunnel effect sensor [4], and optical sensor [5]. Having the properties of chemical inertness and immunity to electromagnetic interference, light weight, and small size, optical sensors can work in strong electromagnetic filed and achieve high spatial resolution and sensitivity [6]. With these advantages, optical waveguide based tactile sensors have been rapidly developing driven by the development of robotics and photonics technologies. Some pioneer work directly embeds conventional optical fiber Bragg gratings [7], ring resonator cavities [8], as well as optical fiber Fabry–Pérot cavities [9] inside elastomers for pressure sensing. One challenge of these sensors is that they need bulky interrogators, which make them difficult for integration. Contrarily to conventional optical waveguide devices, such as optical fibers, which are mainly designed for telecommunication applications, soft optical waveguides are made of transparent elastomers and can be connected to micro-sized LEDs and photon detectors. Such waveguides rely on deformation-induced optical loss are very sensitive

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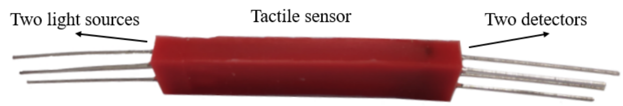
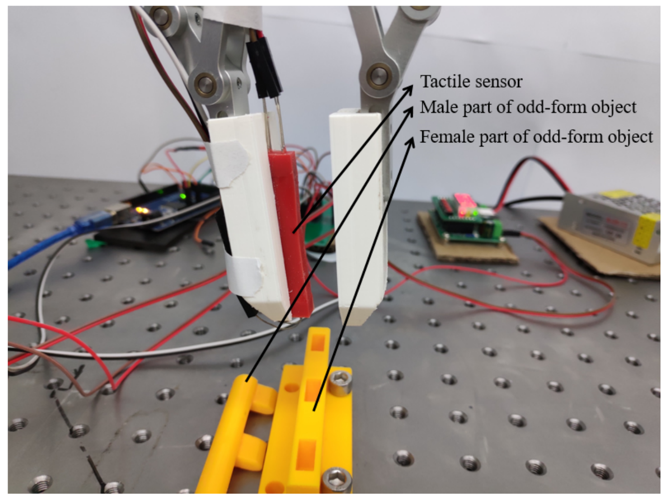


(a)



(b)

Fig. 1: The tactile sensor (a) based on optical waveguide with double-layer cores ($5 \times 9 \times 48\ \mathrm{mm}^3$ in this figure) and (b) mounted on a two-finger gripper in an odd-form plug-in operation.

to pressure [10]. Different types of optical waveguide arrays have also been developed for simultaneous pressure and position detection, such as crossing type [11], lithography type [12] and tunnel-junction type [13]. These sensor arrays currently need abundant detectors (the numbers of sensing points and detectors are of the same order of magnitude), and their sensing areas are physically discontinuous, which need to be further improved in future investigations.

In this paper, we propose a novel waveguide design using a dual-core design, as shown in Figs. 1a and 2a, which can simultaneously measure the normal contact force and any contact position continuously along the waveguide. The waveguide has two layers of cores, which have uniform and incremental widths, respectively. A detector is attached to each core to monitor the internal light power. The contact force and position information can be decoupled and derived from the light power losses in the two cores. In comparison with the present optical waveguide arrays [11], [12], [13], though one piece of the proposed sensor can detect positions in only one dimension rather than two dimensions, its sensing area is physically continuous, which is the advantage that present optical waveguide arrays do not possess. Furthermore, since the proposed waveguide can measure the contact force and position in one dimension with two detectors, if we make a two-dimensional waveguide array by arranging multiple such waveguides side by side, it has the potential in reducing the required number of detectors in comparison with some current waveguide array design [11], [12], [13]. The details for fabricating and calibrating the proposed waveguide are provided within this paper for interested readers to reproduce it.

The paper is organized as follows. Section II presents the principle and novel structure of our dual-core waveguide. Section III introduces its fabrication and calibration. In Section IV, we verify the effectiveness of our sensor design through experiments. Finally, limitations and future work are discussed in Section V.

II. Working Principle

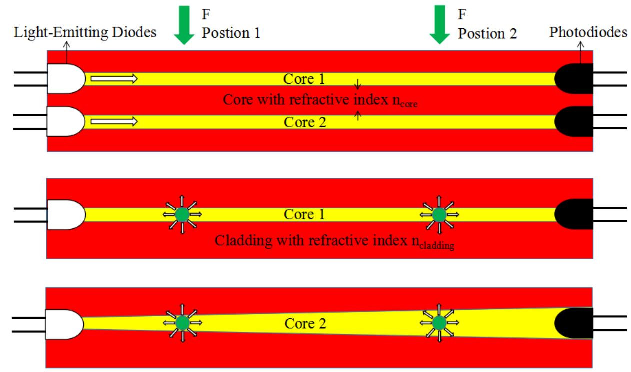
In this section, we explain how our waveguide with two layers of cores can simultaneously measure the normal contact force and the contact position in one dimension.

A waveguide is a tube that guides and conveys waves including the light in our case. When the light propagates through a waveguide, some light may escape from the waveguide to the environment depending on the waveguide's deformation. Initially, we can make a waveguide as straight as possible to attain the minimal light loss. Then, the more the waveguide deforms, the more light escapes. Hence, the light loss can be used to characterize the waveguide's deformation induced by a press. Let P_0 denote the output power of the waveguide with no deformation as the baseline power and P the current output power. The light power loss L in decibels is academically defined as [14]

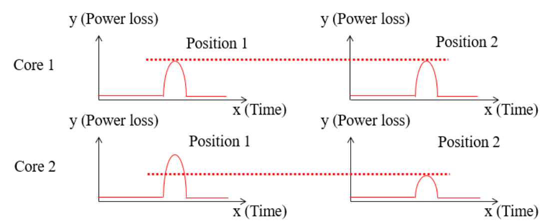
$$L = 10 \log_{10} \frac{P_0}{P} \tag{1}$$

If no press is applied to the waveguide, P is equal to P_0 and the light loss $L = 0$; otherwise, P decreases and $L > 0$.

Our waveguide is composed of two soft cores with a high refractive index n_{core} and the cladding with an elastomer that has a relatively lower refractive index $n_{cladding}$, as depicted in Fig. 2a. The refractive indices n_{core} and $n_{cladding}$ are intentionally close ($n_{core} > n_{cladding}$) to make this waveguide lossy. When the dual-core waveguide is pressed, the light losses in both cores will rise up. Since the width of Core 1 is constant, as shown in Fig. 2a, a pressing force at any position on the waveguide will cause the same deformation, light path change, and in turn light loss in Core 1. Then, we have a one-to-one correspondence between the pressing force and the light loss of Core 1, which can be calibrated and enables us to measure the force directly by the light loss in Core 1. As for Core 2, its width gradually increases from the left to the right, as also shown in Fig. 2a. Although the same force causes the same deformation, the percentage of the light path change is greater on the left side than on the right side such that the light loss is larger if the force is applied at Position 1 than that at Position 2,



(a)



(b)

Fig. 2: Illustration of the waveguide's structure and the relationship between light loss and position under the same force. (a) Structure of the waveguide with double-layer cores. The same force F is applied at Position 1 or 2. Top: Cross section of the waveguide with double-layer cores in the front view. The waveguide includes Core 1, Core 2 and the cladding. Light enters the waveguide horizontally from LEDs on the left side and will be detected by photodiodes on the right side. Middle: Cross section of Core 1 in the top view. Core 1 has uniform width. Bottom: Cross section of Core 2 in the top view. The width of Core 2 is incremental. (b) Light loss under the same force F applied at Position 1 or 2.

as depicted in Fig. 2b. Hence, given a certain force value which can be measured from the light loss in Core 1, we can calibrate the relation of the contact position to the light loss in Core 2. Moreover, we can set up such relations for various force values in a certain range such that the contact position can likewise be derived under any contact force in the range. Using this dual-core design, the waveguide can realize a simultaneous and continuous measurement of contact force and position along it with only two detectors, which are attached to and receive the light from the two cores.

III. Fabrication and Calibration

In this section, we introduce the fabrication and calibration processes of our dual-core waveguide.

A. Fabrication Process

The material of cores is a transparent rubber (Vytaflex 20, Smooth-On Inc.) with the refractive index $n_{\text{core}} \approx 1.46$ at a wavelength of 850 nm. The clad's material is a silicone rubber (SYLGARD 184, Dow Corning) with dark red silicone paste and its refractive index n_{cladding} is around 1.41 at a wavelength of 850 nm. The silicone paste is highly

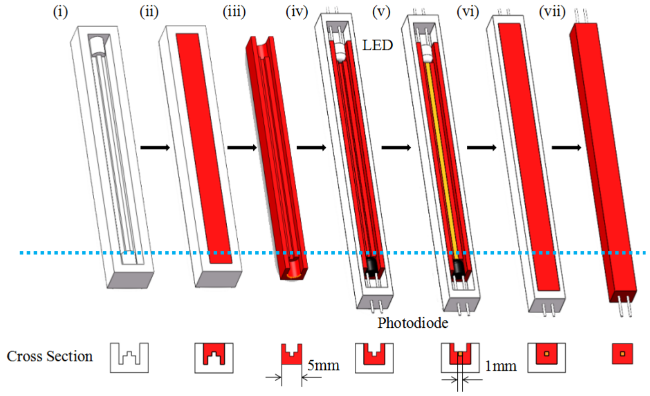


Fig. 3: Illustration of the fabrication of a waveguide with an uniform-width core. The cross section at the blue dotted line is shown at the bottom of this figure.

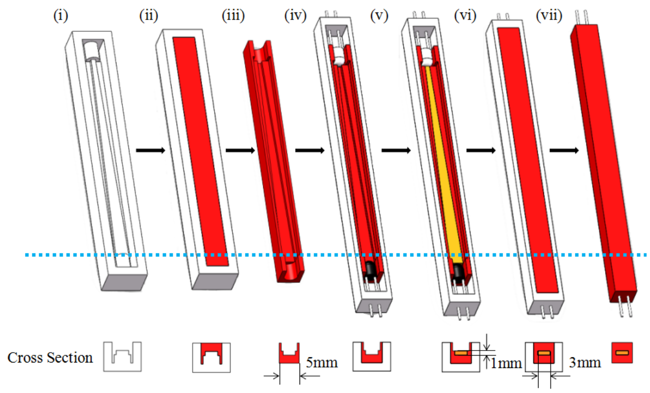


Fig. 4: Illustration of the fabrication of a waveguide with an incremental-width core. The cross section at the blue dotted line is shown at the bottom of this figure.

light-absorbing at the 850 nm wavelength and can reduce the interference between the scattered light in the two cores.

The fabrication of our dual-core waveguide has three steps: a) fabrication of the waveguide with an uniform-width core, b) fabrication of the waveguide with an incremental-width core, and c) integration into the waveguide with double-layer cores. Below we introduce each step in more detail:

- **Fabrication of the waveguide with an uniform-width core (see Fig. 3)**:
  (i) Three-dimensionally (3D) print a mold to make the cladding. The printer is ProJet MJP 2500 of 3D Systems Inc..
  (ii) Degas the pre-elastomer (SYLGRAD 184 with dark red silicone paster) and then pour it into the mold.
  (iii) Heat the mold in $100°C$ for 4 hours to cure the elastomer completely. And then demold the cladding from the mold. The cross section of the cladding is a slotted square. The width of the square is 5 mm.
  (iv) Put the cladding into another 3D printed mold and fix a infrared LED and a photodiode at both ends of the cladding respectively. The diameters of the LED and photodiode are both 3 mm.
  (v) Fill the cladding with the pre-elastomer of the core material (Vytaflex 20) and heat the mold in $100°C$ for 30 minutes to cure the core. The cross section of the core is a square. The width of the square is 1 mm.
  (vi) Pour the pre-elastomer (SYLGRAD 184 with dark red silicone paster) on the core to make the waveguide flat.
  (vii) Heat the mold in $100°C$ for 4 hours to cure the elastomer completely. And then demold the waveguide from the mold.
- **Fabrication of the waveguide with an incremental-width core (see Fig. 4)**:
  (i)-(vii) The same as steps i-vii in Fig. 3, respectively. However, the cross section of the cladding in Fig. 4 (iii) is a slotted square whose width gradually increases from 1 to 3 mm.
- **Integration into the waveguide with double-layer cores.** (see Fig. 5):
  (i) Correspond to Figs. 3 (v) and 4 (v).
  (ii) Demold the half-finished single-layer waveguides from molds.
  (iii) Cut 1 mm thickness off single-layer waveguides to make the following double-layer waveguide thinner.
  (iv) Flip waveguides with a single core 90° and place them face to face into a mold. The cross section of the mold groove is $9 \times 5\ \mathrm{mm}^2$.
  (v) Degas the pre-elastomer (SYLGRAD 184 with dark red silicone paster) and then pour it into the mold.
  (vi) Heat the mold in $100°C$ for 4 hours to cure the elastomer completely and then demold the double-layer waveguide from the mold.

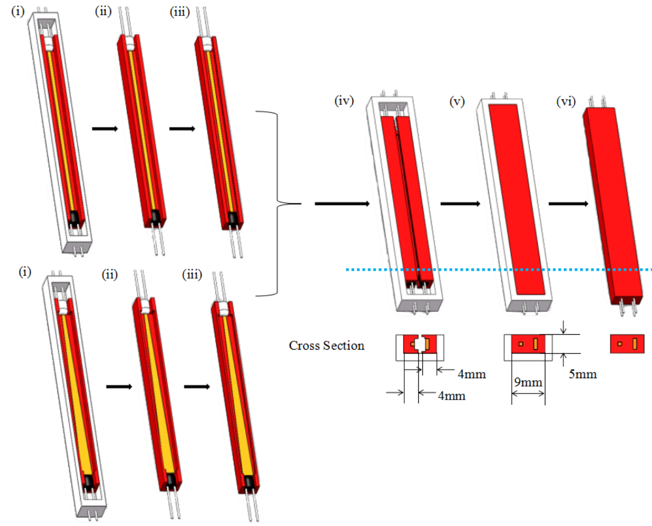


Fig. 5: Illustration of the integration of two waveguides with a uniform-width core and an incremental-width core respectively. The cross section at the blue dotted line is shown at the right bottom of this figure.

B. Calibration Process

Figure 6 depicts our calibration process. A 3-D XYZCVL650-1-1-C-N moving platform from MISUMI Inc. is used to control where and how deep a waveguide is to

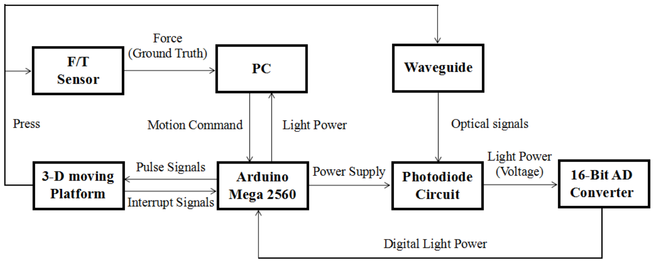


Fig. 6: Diagram of the calibration setup.

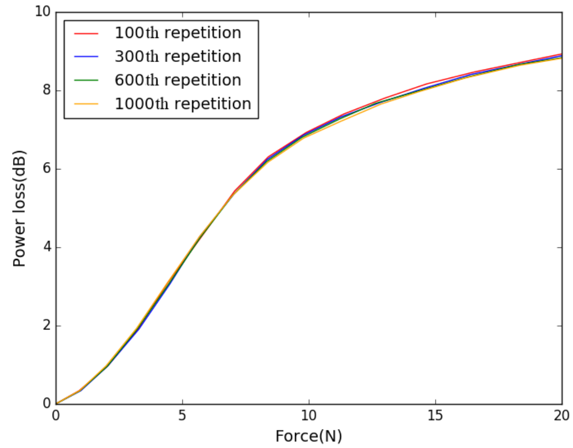


Fig. 7: Repeatability of a waveguide with an uniform-width core. The curves of power loss versus force in four trials are plotted in four different colors and they are nicely coincident.

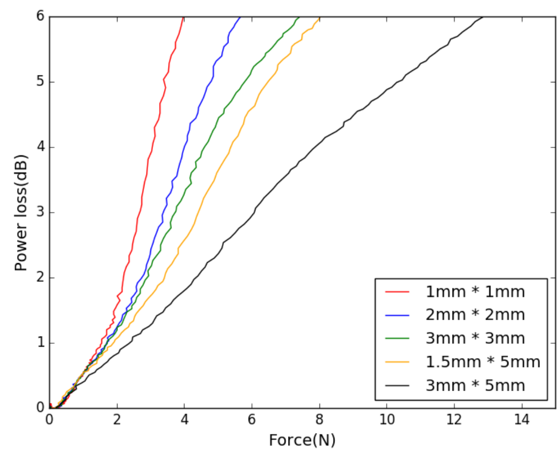


Fig. 8: Response of a waveguide with an uniform-width core pressed with different contact areas.

be pressed. Its maximum moving distance is 50 mm and repeated location error is less than 5 μm in each direction. Each motion direction is controlled by a five-phase stepper motor and the minimum distance for a single move is 2 μm. An M3701A F/T from Sunrise Instruments is used to measure the normal force as the ground truth. Its capacity and resolution are 50 and 0.1 N, respectively. The hysteresis and non-linearity are both 1%. Once the light from the waveguide is detected by photodiodes, the optical signal will be converted into a voltage signal by the photodiode circuit board. The signal-to-noise ratio of this circuit is larger than 1000 when the photodiode is placed in the dark. Programs running on the PC send motion commands to the 3-D moving platform and record the force measurement from the F/T sensor and the light power data from the photodiode circuit board.

IV. Experimental Validation

To evaluate the effectiveness of our waveguide design, we first quantitatively test the performance of our waveguide with a single core with either uniform or incremental width including its repeatability, loss-force curve under different contact areas and loss-force curve under different contact positions. Then, we verify the performance of our double-layer waveguide through the loss-force curve under different positions. Finally, we show the application of our double-layer waveguide in an assembly task.

A. Test of the waveguide with single-layer core

1) Repeatability: Here we let an object with 1.5×3 mm^2 surface area press the middle of a waveguide with an uniform-width core. The 3-D moving platform is used to control this pressing-down action for 15 successive steps with a step size of 200 μm. The PC records the pressing force and light loss data at every step. We try this process for 1000 times and plot the relation of the light loss to the pressing force in four trials is depicted in Fig. 7. It can be seen that the curves are highly overlapping, which implies that the waveguide has a good repeatability.

2) Performance under different contact areas: We now use objects with different contact areas to press the waveguide with an uniform-width core. In each trial, the waveguide is pressed for 150 steps with a step size of 20 μm. Figure 8 plots the result. which shows that a greater contact area leads to a lower power loss. This implies that we can change the sensitivity of the waveguide by changing its dimensions to fit the working range of a particular application.

3) Performance under different contact positions: We use an object with a contact area of 1.5×5 mm^2 to press waveguides with an uniform-width core and an incremental-width core, respectively. The loss-force curves of the uniform-core waveguide pressed at different positions are plotted in Fig. 9a, in which 0 represents the middle of the waveguide. We collect the force-loss data every 2 mm and obtain totally 7 curves. The result shows that the loss-force curve of the waveguide is almost the same at different positions, which implies that the pressing force can be estimated from the light loss of the uniform-core waveguide no matter where it is pressed. Figure 9b shows the loss-force curves of the incremental-core waveguide at different positions. While the waveguide is pressed where the core is smaller, the same force causes a greater light loss and the loss-force curve becomes steeper. Therefore, using this property together with

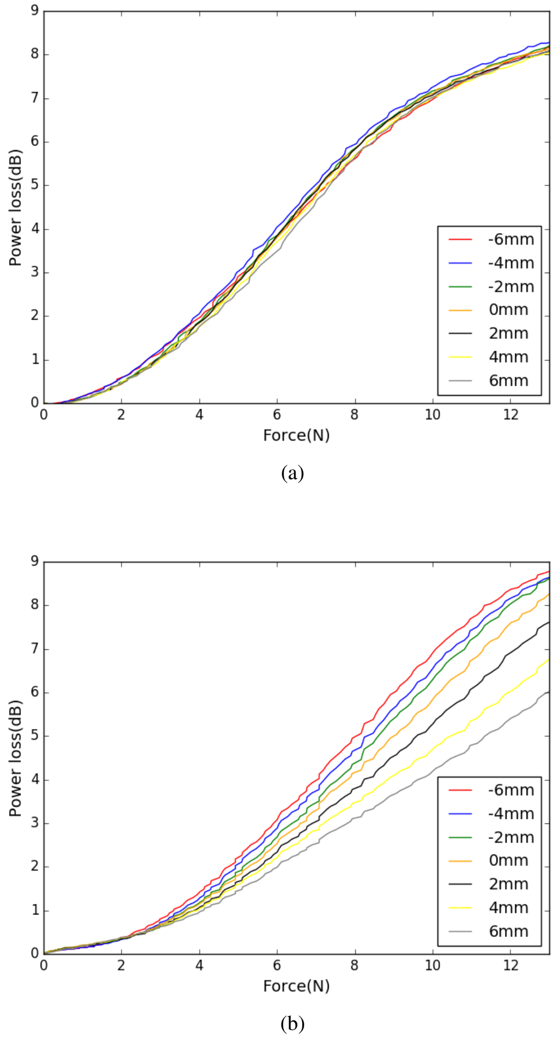


Fig. 9: Responses of (a) a waveguide with an uniform-width core and (b) a waveguide with an incremental-width core pressed at different contact positions.

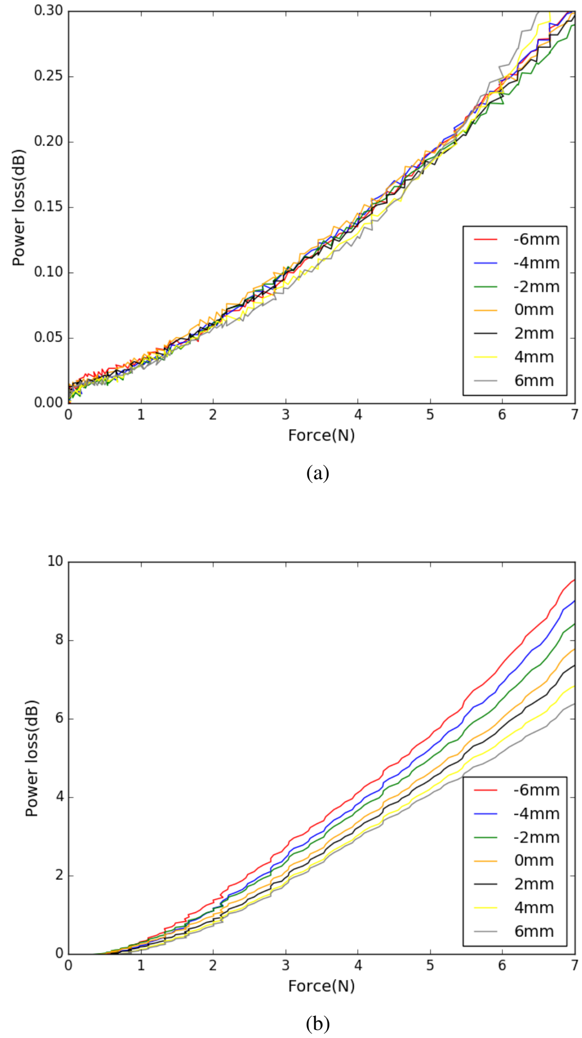


Fig. 10: Responses of (a) the uniform-width core and (b) the incremental-width core of an integrated double-layer waveguide.

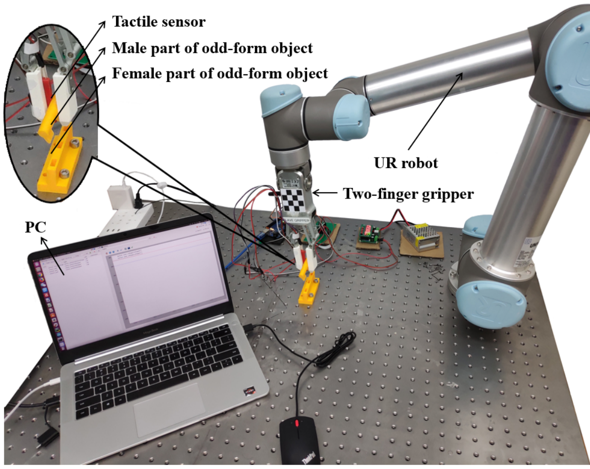
the force measured by the uniform-core waveguide, we can estimate the position of contact.

B. Test of the waveguide with double-layer cores

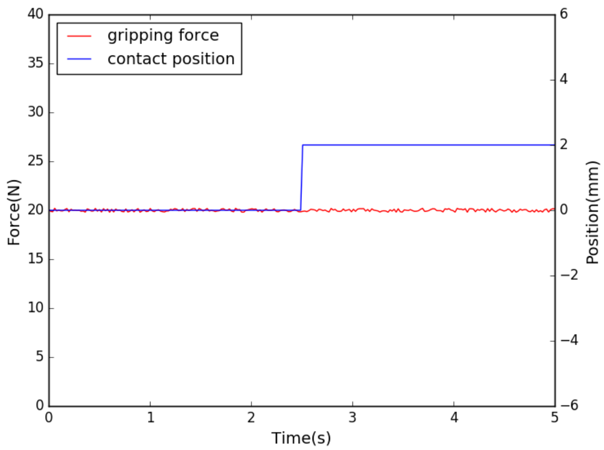
Figure 10 shows the performance of our integrated waveguide including the lower layer with an uniform-width core and the upper layer with an incremental-width core. The waveguide is pressed in the same way as in the previous test of individual waveguides and the result here is similar to the previous one as shown in Fig. 9. However, the waveguide with double-layer cores is 9 mm thick and the deformation of the lower layer is much smaller than in the test of the waveguide with single-layer core.

C. Application Demonstration

To further demonstrate the advantages of this novel tactile sensor and show its potential applications, we apply the sensor to a challenging assembly task, odd-form plug-in assembly, which widely exists in the 3C (Computer, Communication and Consumer Electronic) industry and highly demands the robotic automation. Figure 11a shows such a scenario, which comprises a Universal Robot (UR), a two-finger gripper mounted on the UR robot, the developed tactile sensor attached to the finger tip, and a pair of odd-form objects. During the plug-in process, the main challenge is how to detect the transient failure states when the plug-in is ongoing so as to adjust the pose and action of the end-effector. Also, the electronic components must be gripped gently in order to avoid any damage. Common failure states include the slippage of the male part during the plug in and the insufficient depth of the dose. Since our tactile sensor can provide the normal gripping force and position simultaneously (the spatial resolution is 2 mm and sensitivity is 0.1 N), the aforementioned transient states can be detected immediately. Furthermore, the new contact position between the gripper finger and the male part is monitored. As shown in Fig. 11b, the red line depicts the gripping force (about 20



(a)



(b)

Fig. 11: Application of the proposed tactile sensor to odd-form plug-in assembly. (a) Experimental setup. (b) Plot of sensor readings.

N), while the blue line depicts the contact position, which slipped for 2 mm during the plug-in process. The detected gripping force and contact position can be used as feedback for the controller to increase the gripping force and tilt the gripper to achieve a successful plug-in operation. The plug-in process has been shown in the accompanying video.

V. Conclusion and Future Work

In this paper, we propose a novel tactile sensor design using a waveguide with double-layer cores such that the contact force and the contact position can be measured simultaneously and continuously along the sensor with two detectors. Its fabrication and calibration processes are introduced and preliminary experiments results are provided.

We notice that the current design is still one-dimensional and somewhat thick (9 mm). Our future work will be aimed at resolving these limitations and some improvements have already been in progress. We have actually built a piece of waveguide-based film by lithography, as shown in the accompanying video, and are able to construct a practical sensor by the same principle proposed in this paper. Since we can make the core very thin (< 1 mm) by lithography, one-dimensional waveguides can be arranged side by side to form a two-dimensional sensor. Furthermore, we can use not only light intensities but also wavelengths and phases of light signals to derive useful contact information. When the waveguide-based sensor is extended to two dimensions, it is possible to analyze the intensity and wavelength of the light signal from one fiber to estimate two-dimensional single-layer waveguide's compression. All information can be extracted from the sensor by a single wire (optical fiber). This is not possible for present tactile sensor arrays (e.g., the information of n^2 sensing points needs to be extracted from the sensor by $2n$ wires [1]). This minimal wire layout is extremely needed in the development of some robotic systems, such as robot hands, where the wiring space is limited.

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