Transparent and flexible force sensor array based on optical waveguide

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Abstract: This paper suggests a force sensor array measuring contact force based on intensity change of light transmitted throughout optical waveguide. For transparency and flexibility of the sensor, two soft prepolymers with different refractive index have been developed. The optical waveguide consists of two cladding layers and a core layer. The top cladding layer is designed to allow light scattering at the specific area in response to finger contact. The force sensor shows a distinct tendency that output intensity decreases with input force and measurement range is from 0 to −13.2 dB.

OCIS codes: (280.0280) Remote sensing and sensors; (280.4788) Optical sensing and sensors; (130.0130) Integrated optics; (130.6010) Sensors.

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1. Introduction

These days, touch sensor is widely adopted as input interface of various electronics devices. One good example is touch screen devices such as smartphone [1], tablet computers [2], KIOSK, and etc. Recently, in order to enrich functions of the touch sensor, a touch panel simultaneously measuring pushing pressure as well as contact is considered as a substitution of conventional touch panel. Especially, it has been reported that pressure based interaction improves usability. For example, there is a possibility that pressure based keyboard improves key clicking performance on a touch screen [3]. Moreover, the touch sensor detecting both instant of contact and magnitude of pressure can be applied to various fields such as robots [4,5], medical systems [6] as well as touch panel [7].

The feature of touch sensor as well as its function has been considered to be a crucial factor to improve feasibility for practical applications. For example, the sensor needs to be transparent if it would be laid on a touch screen device and to be thin and flexible if it would be integrated with curved surfaces of flexible display or robot hand [5]. However, the touch sensor still requires compliant technologies to satisfy flexibility and transparency in aspects of material and sensing structure.

Here, we design a force sensing mechanism based on optical waveguide using transparent flexible prepolymers with different refractive index. This paper describes sensing mechanism based on optical waveguide, material design and force sensor fabrication and performance test result.

2. Design

2.1 Materials

Photocurable highly fluorinated liquid prepolymers with different refractive index were synthesized by following the process reported in reference [9]. 2,3,4,5,6-Pentafluoro styrene and anhydrous *N,N*-dimethylacetamide (DMAc) were purchased from Sigma-Aldrich. Fluorinated triethylene glycol and fluorinated tetraethylene glycol were purchased from Exfluor Research. Decafluorobiphenyl was purchased from Tokyo Chemical Industry.

Prepolymer 1, 2,3,5,6,2',3′,5′,6'-octafluoro-4,4'-bis-[2-(2-{2-[2-(2,3,5,6-tetrafluoro-4-vinyl -phenoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-byphenyl was synthesized by reacting decafluoro-biphenyl (11.8 g) with 2-{2-[1,1-difluoro-2-(2,3,5,6-tetrafluoro-4-vinyl-pheno - xy)-ethoxy]-1,1,2,2-tetrafluoro-ethoxy}-2,2-difluoro-ethanol (26 g, compound A) dissolved in DMAc (60 mL) in the presence of a catalyst, potassium carbonate (15.0 g) for 2 days at 80 °C. The final reaction product was extracted with ethyl acetate (EA) after eliminating the catalyst and purified using a column of EA/hexane (2/1, v/v). The compound A was synthesized by reacting 2,3,4,5,6-pentafluoro styrene (25.0 g) with tetraethylene glycol (50.0 g) dissolved in DMAc (40 mL) in the presence of the catalyst, potassium carbonate (15.0 g) for 1 days at room temperature. The compound A was extracted with EA after eliminating the catalyst and purified using a column of EA/hexane (5/1, v/v). The reactions were carried out under nitrogen environment.

Prepolymer 2, 2,3,5,6,2',3′,5′,6'-octafluoro-4,4'-bis-[2-(2-{2-[1,1-difluoro-2-(2,3,5,6-tetra-fluoro-4-vinyl-phenoxy)-ethoxy]-1,1,2,2,-tetrafluoro-ethoxy)-2,2-difluoro-ethoxy]-1,1,2, 2-tetrafluoro-ethoxy}-2,2-difluoro-ethoxy]-byphenyl was synthesized by reacting decafluorobiphenyl (6.6 g) with 2-(2-{2-[1,1-difluoro-2-(2,3,5,6-tetrafluoro-4-vinyl-phenoxy)-ethoxy]-1,1,2,2,-tetrafluoro-ethoxy}-1,1,2,2,-tetrafluoro-ethoxy)-2,2-difluoro-ethanol (compound B) in the presence of a catalyst, which consists of caesium fluoride (0.3 g) and calcium hydride (2.5 g) for 2 days at 60 °C. The final reaction product was extracted with ethyl acetate (EA) after eliminating the catalyst and purified using a column of EA/hexane (1/5, v/v). The compound B was synthesized by reacting 2,3,4,5,6-pentafluoro styrene (19.9 g) with fluorinated tetraethylene glycol (35.0 g) dissolved in DMAc (80 mL) in the presence of the catalyst, calcium hydride (5.4 g) and cesium fluoride (0.65 g) for 3 days at 80 °C. All reactions were carried out under nitrogen environment. After the eluents were completely removed by a vacuum evaporator, the transparent liquid was dried at 35 °C under vacuum.

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After mixing a photoinitiator (1.5%, CGI 124) solution to each prepolymer, it was filtered through a 0.2 μm Teflon filter. The prepolymer containing the photoinitiator was spin coated on the substrate and then UV crosslinked using a UV lamp with 2 kW power for 10 min. Finally, the prepolymer coating was thermally annealed at 150 °C under nitrogen environment.

Characteristic of both prepolymers were studied in terms of refractive index and elastic modulus. The refractive indices were measured using a prism coupler for a transverse electric field (TE) polarized light at a wavelength of 632.8 nm. Elastic moduli were obtained from their strain-stress curves, which are measured by an Instron 4482 at constant extension rate of 5 mm/min. As shown at Table 1, both prepolymers have remarkably lower elastic modulus (E) than other conventional flexible polymers such as polyethylene terephthalate (PET, E: 2.1 ~4.0 GPa) [8] and polyvinyl chloride (PVC, E: 1.3 GPa) [9], which is an indication of excellent compliance to highly curved structure. On the other hand, the prepolymers retain different refractive index due to the difference in fluorine contents tailing onto the prepolymers. The prepolymer 1 shows higher refractive index than prepolymer 2 since fluorine substitution generally results in a decrease in refractive index [10]. Based on the result, we select a prepolymer 2 with relatively higher fluorine content as cladding layer in order to reduce undesirable diffuse reflection of light propagating in a core layer.

Table 1. Characteristics of the fluorinated prepolymers

Material	Fluorine contents (%)	Refractive index	Elastic modulus (GPa)
Prepolymer 1	29.49	1.5125	0.42
Prepolymer 2	51.96	1.4300	0.44

2.2 Sensor design and manufacturing

The transparent and flexible force sensor array based on optical waveguide can be a compliant technology to realize interactive flexible display since the flexible sensor layer allows diverse user interface at highly curved architecture. We have fabricated the force sensor array with a square shaped key pad in the thin film architecture by following microfabrication process flow illustrated in Fig. 1.

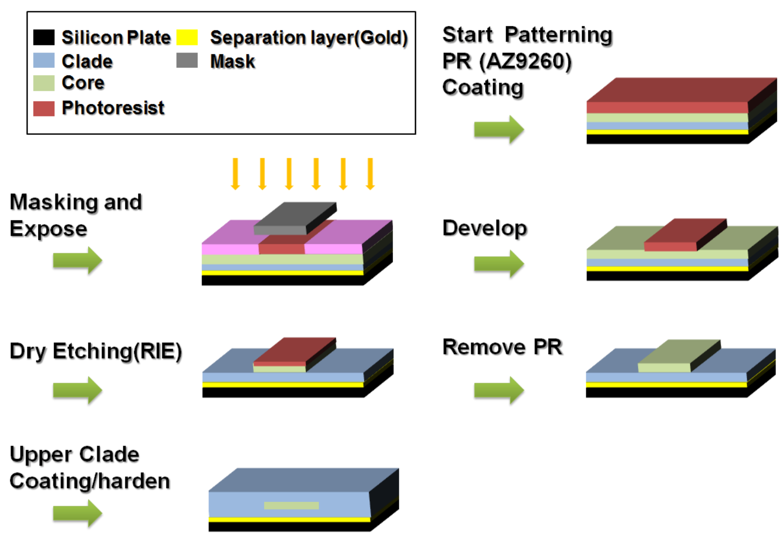

Fig. 1. Microfabrication process for force sensor.

Two fluorinated liquid prepolymers with different refractive index are used for a cladding (prepolymer 2) and a core layer (prepolymer 1), respectively. Each prepolymer forms a thin film on the substrate by spin coating, UV crosslinking and thermal annealing under nitrogen

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environment in sequence. The bottom cladding layer (thickness: 20 µm) is formed on a gold coated silicon wafer and then a core layer (thickness: 10 µm) is stacked on it.

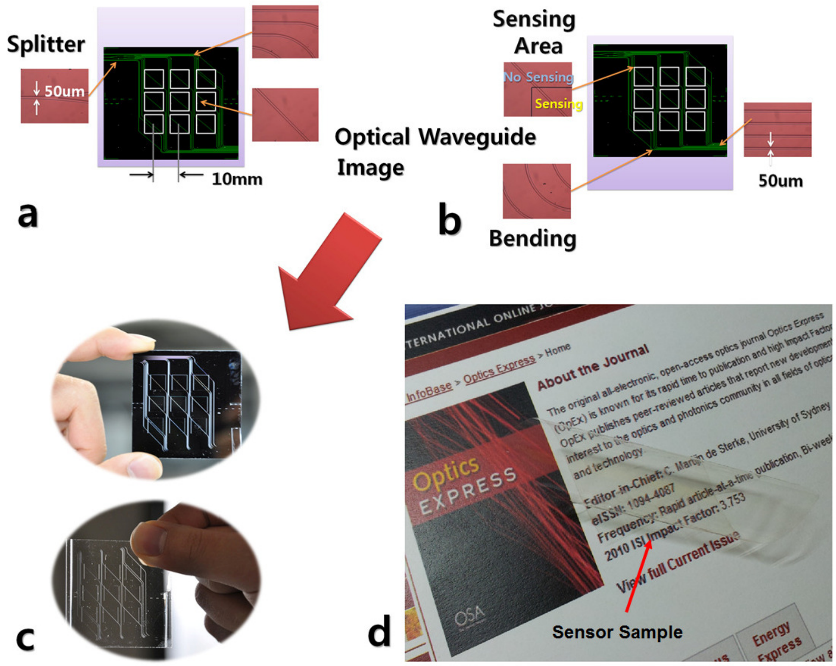

Fig. 2. A configuration of sensor based on optical waveguide.

The thin gold layer works as a sacrifice layer to easily separate the sensor layer from the silicon wafer substrate after fabrication. Top cladding layer pattern (thickness: 20 µm), which is partially opened at specific area for composing sensing area, is fabricated on the core layer via photolithography and dry etching process. Figure 2(a) and Fig. 2(b) show microscopic pictures of optical wave guide designed for the force sensor array with key pad configuration. Figure 2(c) shows intermediate products of the sensor fabricated on a silicon wafer and glass, respectively. Figure 2(d) shows transparency and flexibility of the final product of the sensor.

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2.3 Working principle

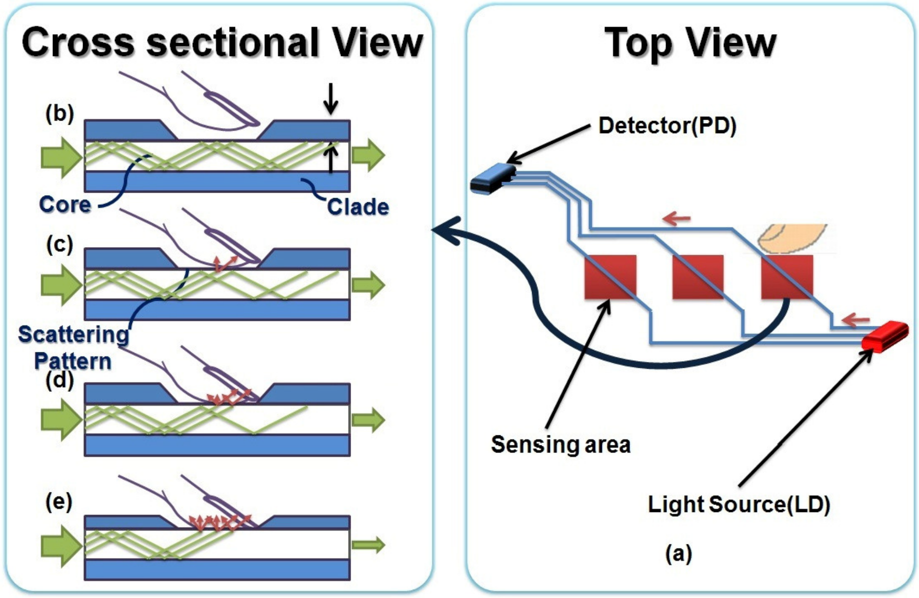

Fig. 3. Working principle of desired force sensor.

A transparent and flexible force sensor with optical waveguide works based on following principles. As shown in Fig. 3, the optical waveguide consists of two cladding layers and a core layer made of soft polymers described in the section 2. As shown in Fig. 3(a) and Fig. 3(b), bottom cladding layer is closed while top cladding layer is opened at the specific area which is a sensing area allowing finger contact. In general, the light inserted in a core layer pass through the core layer and total reflection induced since its reflection index is higher than that of cladding layer or air. However, if human finger touches at the sensing area of the top cladding layer, diffuse reflection and light scattering occurs at the contact area as shown in Fig. 3(c) and the detector composed of photo diodes measures decreased light intensity for each channel. As shown in Fig. 3(d) and Fig. 3(e), when a user increases contact pressure, the contact area between the finger and sensing area increases and diffuse amount of the light also increases. Thus, the transmitted light measured by the detector decreases as the contact pressure increases. Moreover, since the optical waveguide made of polymers allows bending without light scattering and forming a thin film, this sensor could be applied to various surfaces as well as a plat touch screen.

3. Measurement

In order to evaluate performance of the developed force sensor, a measurement system composed of a load cell force sensor, a data acquisition controller and a laptop computer is designed as shown in Fig. 4.

The reference load cell is placed under the force sensor. Since a principal application area of the sensor is tapping force measurement on a touch screen, the load cell with sensing range of 0~50N is selected in order to cover human gentle tapping capability which is smaller than 20N [11,12].

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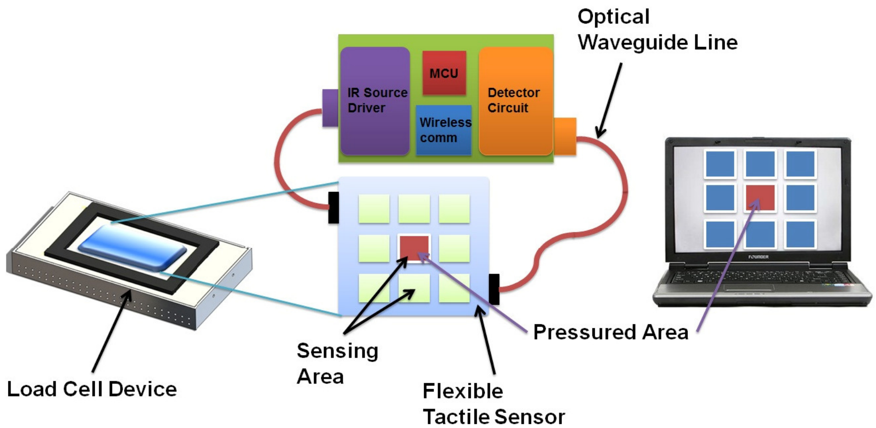

Fig. 4. Schematic overview for measurement.

There is a controller including a light source, 9 output light detectors, a signal processor and a communication module. The source provides infrared light with a wavelength of 850 nm. When a user press the sensor, the controller reads force values from the load cell and intensities of output light simultaneously, and delivers all data to the laptop. All experimental data are recorded in the computer in every 10 milliseconds. The analog to digital converter of the measurement system has a resolution of 12 bits (4096 steps).

In this experiment, the measurement system is presented to all participants in an isolated room and they are requested to press and to release the sensor twice continuously.

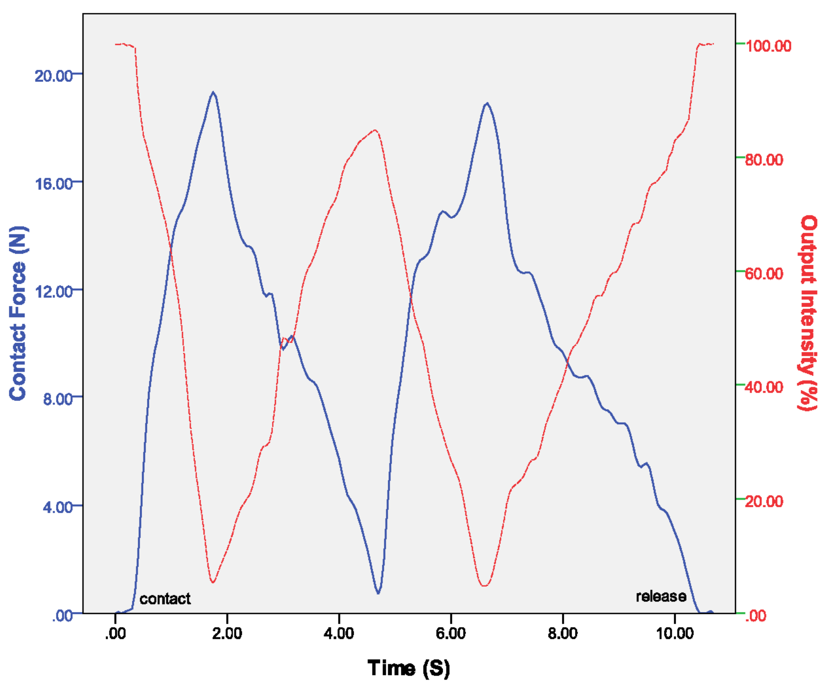

Fig. 5. Contact force versus sensor output intensity according to time.

Figure 5 shows changes of contact force and output intensity according to time while a subject participates in an experimental task. An apparent trend is observed that output light intensity decreases as input pressure increases. (Pierson correlation coefficient between

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contact force and output intensity is −0.936.) In addition, the value of signal to noise ratio (S/N) of the output signal is 97.8.

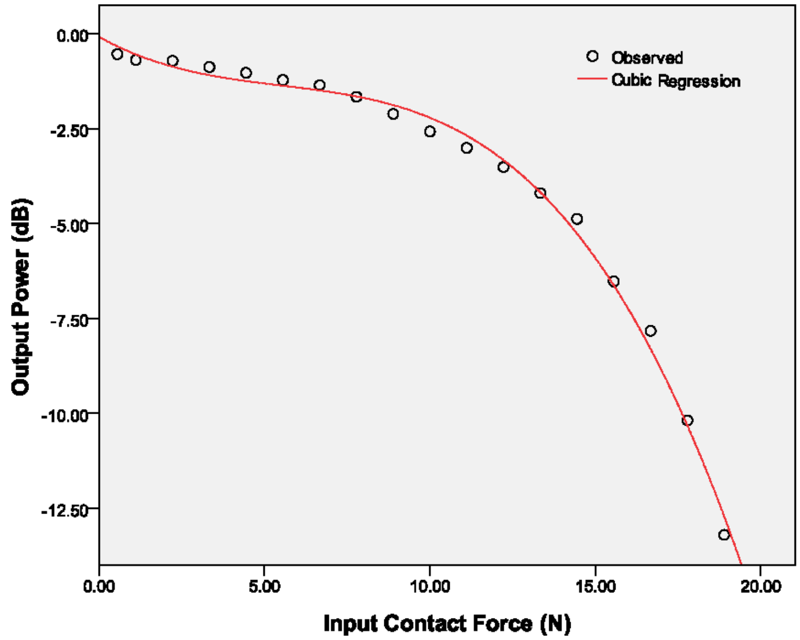

Fig. 6. Sensor output according to input force.

In order to figure out more analytical relation, we looked at data and a cubic regression curve for average user input force and average output light intensity decrement as shown in the Fig. 6. The output power gradually decreases to the level of 4.78% (−13.2 dB) as the input force increases to 18.9 N. It shows a clear tendency that output power is tightly correlated with the finger contact force. Statistically, the R^2 value and standard error for the cubic regression curve are 0.995 and 0.292, respectively. We conclude that the developed sensor can be a promising candidate for flexible force sensor.

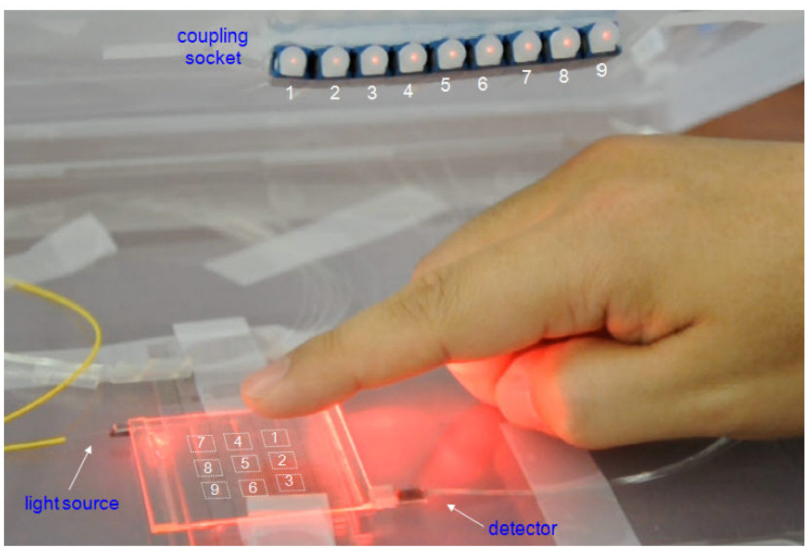

Fig. 7. Demonstration of the sensor (Media 1).

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We prepared supplementary materials describing the change of light intensity according to the pressured sensor by finger (See Fig. 7 and Media 1) in order to show the actual operation of the sensor

We need to consider several issues for feasibility of the sensor. As shown in Fig. 5 and Fig. 6, an initial output signal drop is observed once the finger is contacted surface of the sensor. Although the contact force is too small to be precisely measured by the load cell, instant light scattering about 10% at the moment of finger contact is observed. The second issue is a nonlinear relation between input force and output signal. Since deformation of human finger at the contact surface also has nonlinear characteristics [13], quantified approaches for a structural fingertip model and light scattering simulations regarding the sensor structure will be required. The third issue is hysteresis caused by viscoelastic property of polymers. Hysteresis curve depends on input frequency as well as material property. Since input frequency delivered by human touch is hard to be quantitatively controlled, we don't investigate this aspect deeply at a pilot stage for this paper. But we need to report hysteresis analysis at the application stage after precisely controlled mechanical input test.

4. Conclusion

We have developed a transparent and flexible force sensor based on optical waveguide that can be applied to flexible display as well as conventional touch display. The optical waveguide consists of two cladding layers and a core layer. Novel photocurable prepolymers which are synthesized to be tailed with different fluorine contents are developed for the functional layers since refractive index depends on fluorine contents in the prepolymer. Covering both surfaces of the core layer with cladding layer allows light to passing through the core layer via total reflection due to the difference in refractive index between core and cladding layers. A finger touching at the opened area of the top cladding layer leads to intensive scattering of light propagating through the core layer at the contact area. The force sensor shows a distinct tendency that output intensity decreases with input force and measurement range is from 0 to −13.2 dB. Future studies will focus on establishing user adaptive calibration on our force sensor since its nonlinear response with respect to contact force depends on individuals.

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