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Coil-shaped multimode polymer optical fibers for robotic tactile perception

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Abstract: Optical fiber tactile sensors capable of measuring contact forces are emerging as potential components for intelligent robotics. The demand for innovative fiber sensor designs and effective fabrication techniques to enhance tactile sensing performance is growing. In this study, we propose and demonstrate a robotic tactile sensor utilizing the coiled multimode polymer optical fiber (POF). The fiber coils are formed by winding commercial polymethyl methacrylate (PMMA) optical fibers around a steel needle and applying heat to maintain the coil configuration. The polymer fiber coil is then integrated into polydimethylsiloxane (PDMS) substrates for mechanical support and protection. Under external pressure, the fiber coil deforms, leading to a reduced bending radius and an increase in bending loss. Experimental results show that sensitivity and dynamic range can be adjusted by varying the number of coils. A resolution of 0.024 N and a dynamic range of 0-10 N for the detection of normal force were achieved with a coiled POF featuring a coil diameter of 1.125 mm and a coil quantity of 8.5. Ultimately, we integrated a coiled fiber tactile sensor array onto the finger of a robot manipulator to enhance grasping capabilities, demonstrating its potential for practical applications. The proposed coiled fiber sensor may potentially inspire new sensing devices and find use in smart homes and healthcare.

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1. Introduction

Tactile sensors that replicate the human sense of touch are essential in intelligent robotics. They can perceive external stimuli, such as pressure and force, enabling intelligent robots to interact more efficiently with their environment, thereby enhancing safety, adaptability, and the ability to execute complex tasks [1]. Optical fiber tactile sensors are a promising technology in this domain, demonstrating inherent benefits such as immunity to electromagnetic interference, compact size, and significant flexibility. These sensors predominantly utilize optical fibers to assess tactile interactions via light modulation, providing high sensitivity to force, pressure, and other tactile stimuli [2].

In recent years, a variety of optical fiber tactile sensors have been developed. These sensors can be classified as fiber Bragg grating (FBG) based tactile sensors [3–7], interferometric optical fiber tactile sensors [8–12], and intensity-modulated optical fiber tactile sensors based on the

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sensing mechanism [13–24]. The FBG is a sensor that has been commercialized for temperature measurement and strain sensing and is well-established. Researchers insulated the FBG within polydimethylsiloxane (PDMS) substrates to facilitate force/pressure sensing in order to perform tactile force measurement. Wang Q *et al*. reported and tactile force sensor based on in-line single-few-single mode fiber Mach–Zehnder interferometer with a sensitivity of 26.58 nm/N within the 0–3 N range [11]. Ding Z et al. developed a 2D tactile sensor that utilizes a single multimode optical fiber embedded in a soft silicone rubber substrate. Through multimode interference induced by a 1550 nm laser and deep learning techniques, the sensor achieves over 98% spatial position recognition accuracy at a resolution of 0.5 mm × 0.5 mm, along with nearly 100% accuracy in force sensing at 3 grams [12]. However, all these reported tactile sensors utilized standard silica optical fibers with an outer diameter of 125 µm, and the integration of silica optical fibers into curved surfaces for practical applications was impeded by their brittleness and limited flexibility [3–6].

In order to address this obstacle, tactile sensing devices were constructed using optical micro/nanofibers that were fabricated from standard single-mode silica optical fibers [13–20]. The optical micro/nanofiber, which has diameters that are either equal to or smaller than the wavelength, is highly flexible and highly responsive to external physical parameters, in contrast to the conventional single-mode silica optical fiber, which is brittle. Lei Zhang's group has created a series of innovative tactile sensing devices that are based on optical nanofibers and demonstrate exceptional performance in the area of tactile force sensing. These devices include a single optical nanofiber integrated inside a PDMS film [13,17–18], a bent optical nanofiber encased in a PDMS sphere, and a connected pair of optical nanofibers enclosed within a PDMS film [19]. All these sensors are intensity-modulated type tactile sensors. In the interim, other groups also reported optical microfiber-based FBG tactile sensors [6] and optical nanofiber ring resonator-based tactile sensors [20]. The precise control of the fiber diameter and the safe manipulation of the fiber present the optical micro/nanofiber tactile sensor with a challenge.

Polymer optical fibers (POFs) provide exceptional flexibility and can endure significant deformations. Zhao *et al*. created a small, stretchy POF robotic tactile sensor with an LED and photodetector at either end of the fiber, employed for the detection of surface topography and roughness [21] positioned at various points to distinguish contact force and position [22]. Guo *et al*. developed a versatile hydrogel optical fiber tactile sensor that utilizes color multiplexing for concurrent multi-point pressure detection [23]. Pan J et al. created a knot- inspired optical fiber tactile sensor. By introducing local self-contact points within the POF, this sensor enables sensitive detection of both normal and frictional forces, facilitating slip detection and friction measurement in robotic dexterous manipulation [24]. These tactile sensors, constructed from POF, exhibit elasticity and seamless integration with robotic manipulators, allowing for the detection of external forces and objects, hence enhancing operational intelligence.

We propose and demonstrate a tactile sensor utilizing coiled multimode POF with a three-dimensional spring-like architecture. The sensor utilizes bending-induced optical loss to detect contact force or pressure. Upon the application of an external force to the surface of the PDMS-insulated coiled fiber tactile sensor, the coiled area undergoes deformation, leading to a reduction in the bending radius and an increase in optical loss. We have empirically validated our concept with fiber coils (with a coil diameter of 1.125 mm) constructed from commercial multimode polymethyl methacrylate (PMMA) optical fibers as an example. Experimental findings indicate that sensitivity and dynamic range may be adjusted by altering the number of coils. A normal force resolution of 0.024 N and a dynamic range of 0-10 N were attained using a coiled POF with a coil diameter of 1.125 mm and a coil quantity of 8.5. The sensor has great repeatability and durability for up to 10,000 cycles. A coiled fiber tactile sensor array was ultimately incorporated into the finger of a robot manipulator to improve gripping skills. Our sensor has significant design flexibility and exceptional robustness relative to current fiber optic

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tactile sensing technologies; furthermore, it facilitates mass production, suggesting considerable potential for practical applications.

2. Working principle and fabrication

2.1. Construction and working principle

Figure 1 depicts the configuration of the coiled multimode POF tactile sensor, consisting of two main elements: the spring-like coiled fiber segment functioning as the force transducer and the PDMS substrate providing support and protection for the coiled fiber. The dual pigtails of the POF link the light source and the light detector. Multimode POFs were chosen for the construction of fiber coils owing to their enhanced flexibility relative to silica optical fibers, ease of fabrication into intricate spatial configurations through heat shaping techniques, uncomplicated connectivity to the light source and detector, and cost efficiency. This sensing technique has considerable flexibility since the fiber diameter, coil radius, and coil quantity may all be modified to optimize sensing performance.

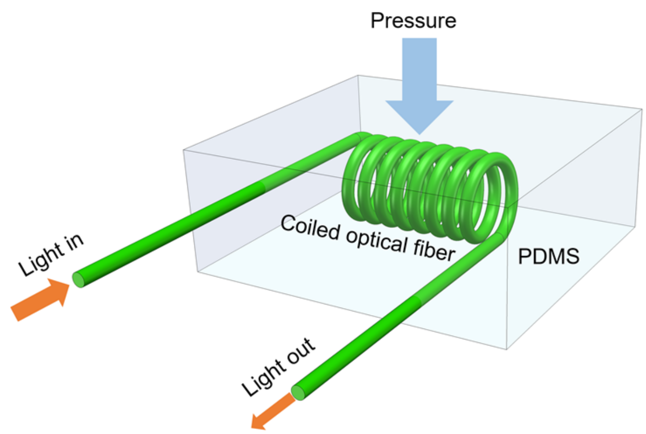

Fig. 1. Schematic diagram of the coiled multimode POF-based tactile sensor.

The primary tactile sensing mechanism of coiled multimode POF is based on bend-induced optical loss, which depends on the bending radius of the fiber coil and is influenced by external forces. To illustrate this process clearly, we focus on a single fiber coil, as shown in Fig. 2(a). When light enters the multimode POF, typically made from PMMA, a multitude of guided core modes can be stimulated and propagated within the fiber core with minimal loss. However, when these modes enter the coiled region, their bending loss efficiency increases, leading to the cutoff of some higher-order modes once the bending radius of the fiber coil reaches a certain threshold. Consequently, the optical fiber coil, without external pressure, exhibits an intrinsic optical loss that depends on both the coil radius and the number of coils. For clarity, in comparison with the fiber coils under external pressure, we do not depict the light rays escaping from the bending fiber that correspond to this intrinsic bending loss.

As depicted in the lower section of Fig. 2(a), when the fiber coil is subjected to external pressure, it experiences deformation, leading to a reduction in the bending radius on both the left and right sides of the fiber coil. This results in an exacerbation of bending loss for the guided modes, with certain additional modes becoming cutoff. While the bending radius on the top and lower sides of the fiber coil increases, resulting in reduced bending loss, the total optical loss for the coiled fiber tactile sensing device escalates. The total bending of the fiber coil logically rises with the rise in external pressure. The pressure and contact force exerted on the coiled multimode

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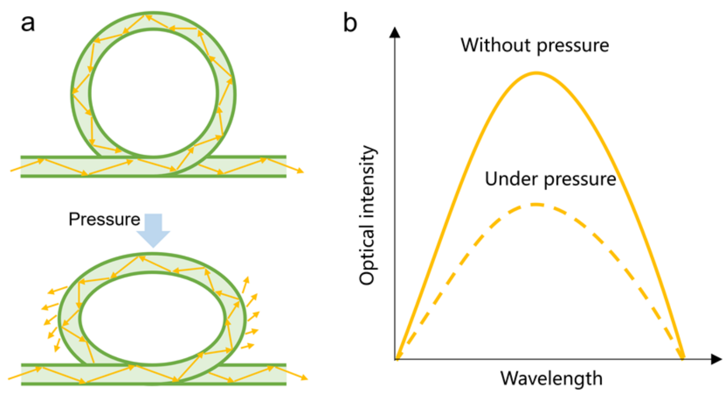

Fig. 2. (a) Tactile sensing principle of the coiled multimode polymer optical fiber. (b) Typical spectral response of the sensor to pressure.

fiber-based tactile sensor may be quantified by only observing the output optical power, as seen in Fig. 2(b). The sensitivity is anticipated to enhance with an increase in the number of fiber coils.

2.2. Sensor fabrication and characterization

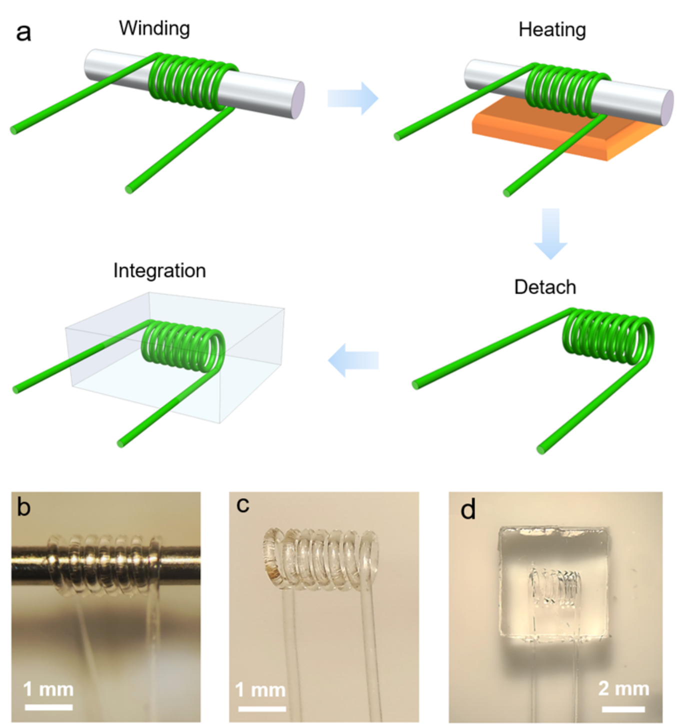

Fig. 3. (a) Procedures for the fabrication of the coiled multimode POF tactile sensor. (b) Photograph of a coiled POF wrapped around a steel rod. (c) Photograph of a freestanding coiled POF. (d) Photograph of coiled POF embedded into PDMS.

We devised a four-step procedure to build a coiled multimode POF tactile sensor, as seen in Fig. 3(a). A segment of multimode POF is initially wound around a steel rod of specified diameter to create a spring-shaped fiber coil including many turns. The polymer fiber coil, curved like a spring, was positioned on a heated plate at 120° C, alongside the steel rod, to eliminate internal tension and preserve the coil configuration for the POF. The fiber coil was cooled to ambient temperature and detached from the steel rod. Finally, the coiled multimode POF was enclosed within PDMS substrates for integration.

In our investigation, we utilized commercial PMMA optical fibers, including a 240 µm-thick PMMA core (refractive index: 1.49) and a 5 µm-thick PVDF cladding (refractive index: 1.42), together with a steel rod of 1.0 mm diameter to construct the polymer fiber coil. The diameter of the fiber coil is approximately 1.125 mm. Figure 3(b) shows an image of a polymer fiber coil, consisting of 6.5 turns, around a steel rod. Figure 3(c) depicts an image of the liberated free-standing POF coil detached from the iron rod. The fiber coil was submerged in PDMS precursors at a ratio of 10:1 and cured at 60°C. Figure 3(d) presents an image of the resulting coiled multimode polymer tactile sensor. This fabrication method enables the production of coiled POF tactile sensors with specified coil diameters and quantities, utilizing a range of POF and elastomers (such as rubber and polyurethane) with varying mechanical properties, thereby rendering the proposed sensing scheme highly versatile and adaptable for diverse applications.

3. Results and discussion

3.1. Tactile sensing performance

Then, we examined the sensing properties of the tactile sensor composed of a coiled multimode POF. PDMS substrates were used to encapsulate coiled POF with coil numbers of 2.5, 3.5, 6.5 and 8.5. The compact tactile sensors that resulted have dimensions of 5 mm × 5 mm × 3 mm. Afterward, we mounted the coiled POF tactile sensors on a force-testing apparatus and sequentially examined the sensors' tactile sensing capabilities, as illustrated in Fig. 4. A motorized translation stage, a force gauge, and a testing probe constitute the force measurement apparatus. Through the testing instrument, the force was applied to the coiled fiber tactile sensor, and the force gauge monitored the force in real-time. In order to perform optical measurements, the two pigtails of the sensor were connected to a broadband white light source (Ideaoptics, HL2000) and a potable spectrometer (Ideaoptics, FX2000). The force applied to the sensors was gradually increased from 0 N to 10 N, with a 2 N interval between each increase.

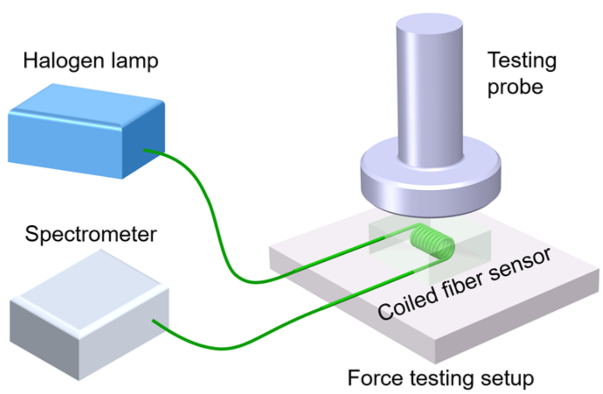

Fig. 4. Schematics of the setup used to apply the force on the coiled fiber tactile sensor.

Figure 5(a) illustrates the typical normalized transmission spectrum of a coiled POF tactile sensor with 2.5 coils in response to external forces. It is evident that the normalized intensity at all wavelengths decreases significantly as the force increases from 0 N to 10 N, thereby illustrating the ability of the proposed sensor to measure tactile force efficiently. All wavelengths within the range of 450 nm to 850 nm exhibit analogous responses to external normal force, indicating that narrowband light sources such as lasers or LEDs may be utilized as the light source. The spectral responses of the coiled POF tactile sensor with coil counts of 3.5 6.5 and 8.5 are also illustrated in Fig. 5(b), 5(c) and 5(d), respectively. These tactile sensors with larger coils numbers all show good response to external forces and All wavelengths within the range of 450 nm to 850 nm exhibit analogous responses. Notably, the sensor with a greater number of fiber coils exhibits a higher response amplitude.

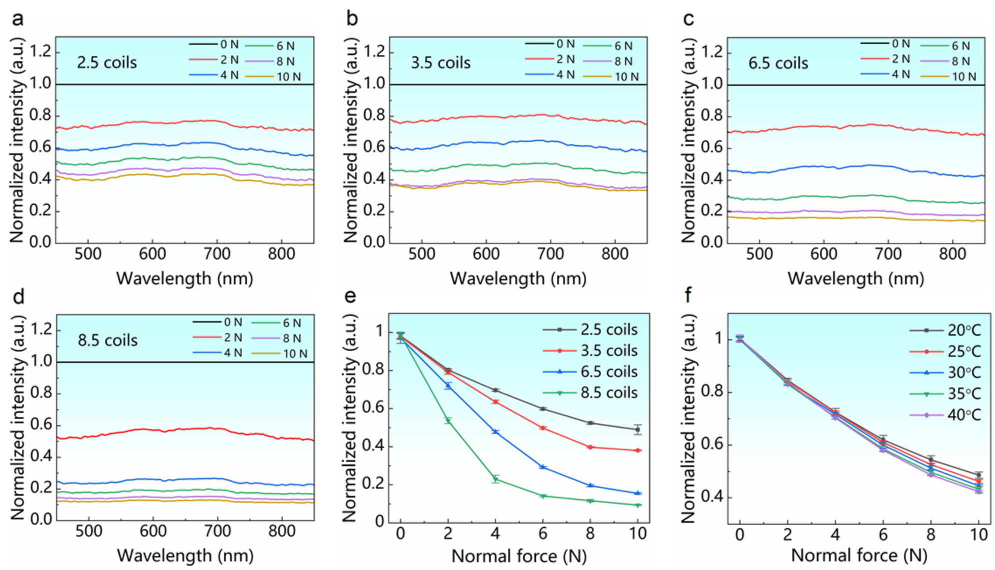

Fig. 5. (a) Normalized spectra of a 2.5-coil multimode POF tactile sensor. (b) Normalized spectra of a 3.5-coil multimode POF tactile sensor. (c) Normalized spectra of a 6.5-coil multimode POF tactile sensor. (d) Normalized spectra of an 8.5-coil multimode POF tactile sensor. (e) The normalized light intensities at the wavelength of 650 nm for the coiled multimode POF tactile sensor with coil counts of 2.5, 3.5, 6.5 and 8.5. (f) Sensing performance of 2.5-coil multimode POF tactile sensor at different ambient temperatures.

The normalized transmission value of wavelength 650 nm for all three sensors was plotted in Fig. 5(e) to facilitate a clear comparison. It demonstrates that a coiled multimode polymer tactile sensor with a higher number of coils is more susceptible to external forces. This is primarily due to the fact that the sensing mechanism is predicated on the deformation loss that is caused by pressure. Therefore, the presence of a greater number of fiber coils results in a greater number of bending sections and, as a result, larger response signals.

The primary indicators for assessing a tactile sensor are sensitivity, force resolution, and dynamic range. The POF tactile sensor with 8.5 coils has a sensitivity of 0.211 N^{-1} and a force resolution of 0.024 N within the range of 0–2 N, and a dynamic range of 0–10 N, assuming a signal-to-noise ratio of 200:1 for the spectrometer. Because the previously described optical fiber tactile sensors use different detecting techniques and have varying sensitivity, we will simply compare the force resolution and dynamic range of the coiled multimode polymer tactile sensor to those previously reported. The force resolution of the 8.5 coil polymer fiber tactile sensor is somewhat higher than the arc-shaped micro-fiber Bragg grating sensor (resolution: 0.01 N) [7] and the all-in-fiber Match-Zehnder interferometer (resolution: 0.015 N, dynamic range: 0–1 N) [8]. But the dynamic range is much larger than the all-in-fiber Match-Zehnder interferometer. In comparison to well-established optical micro/nanofiber tactile sensors, which generally have force resolutions of less than 1 mN [16,18], the suggested sensor has a rather high resolution. However, the suggested sensor's relatively high dynamic range makes it suitable for robotic

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manipulator applications. Compared to the stretchable POF tactile sensor proposed by Bai H. et al., which has a normal force resolution of 0.14 N [22], our sensor exhibits a finer resolution. In comparison to the knot-inspired POF tactile sensor [24], our sensor demonstrates a similar force resolution. However, our sensor features a significantly smaller footprint, indicating its potential for high spatial resolution tactile sensing.

To investigate the effect of ambient temperature on the sensing performance, the sensor was placed in a homemade thermostat box for pressure testing. Figure 5(f) shows the change in normalized intensity at a wavelength of 650 nm for the coiled POF sensor (with 3.5 coils) in response to normal forces ranging from 0 to 10 N at different ambient temperatures (from 20°C to 40°C, with increments of 5°C). The overlapping trends across different temperatures suggest that the sensor performs well within the temperature range of 20°C to 40°C. The results also indicate that as the temperature increases, the sensitivity of the sensor slightly increases. This may be due to the decrease in Young's modulus at higher temperatures, which causes the sensor to undergo greater deformation under the same applied pressure.

Subsequently, we conducted a reliability and durability assessment of the coiled multimode POF tactile sensor under a cyclic loading-unloading signal with a force amplitude of 5.0 N. Figure 6(a) illustrates the experimental configuration for the assessment. Figure 6(b) illustrates the real-time response signal of the sensor across 10,000 cycles of loading and unloading activities. The consistent and unwavering amplitude of the output optical signal illustrates the remarkable endurance and stability of the coiled multimode POF tactile sensor, signifying its suitability for prolonged usage in everyday applications.

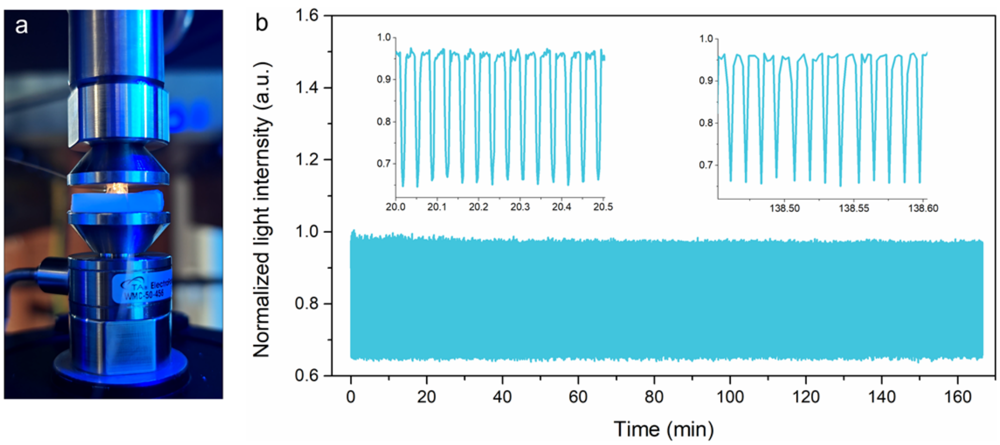

Fig. 6. (a) Photograph of the experimental setup for the reliability and durability testing. (b) The reliability and durability performances of the coiled multimode POF tactile sensor subjected to a cyclic loading-unloading signal with an amplitude of 5.0 N over 10,000 cycles.

3.2. Application in robot manipulator

In order to verify the potential of the designed tactile sensor in practical applications, we fabricated a tactile sensor array using four coiled multimode POF and integrated it onto one fingertip of a 2-finger adaptive robot gripper (DH-robotics, AG-105-145) to assist in grasping objects. Here, we designed the sensor array to demonstrate the compactness of the proposed sensor and the ability to perceive force distributions on a contact interface. Figure 7(a) illustrates a typical image of the sensor array, which comprises four sensing devices known as s1, s2, s3, and s4. Figure 7(b) illustrates the robot gripper that is incorporated with the sensor array on a single fingertip.

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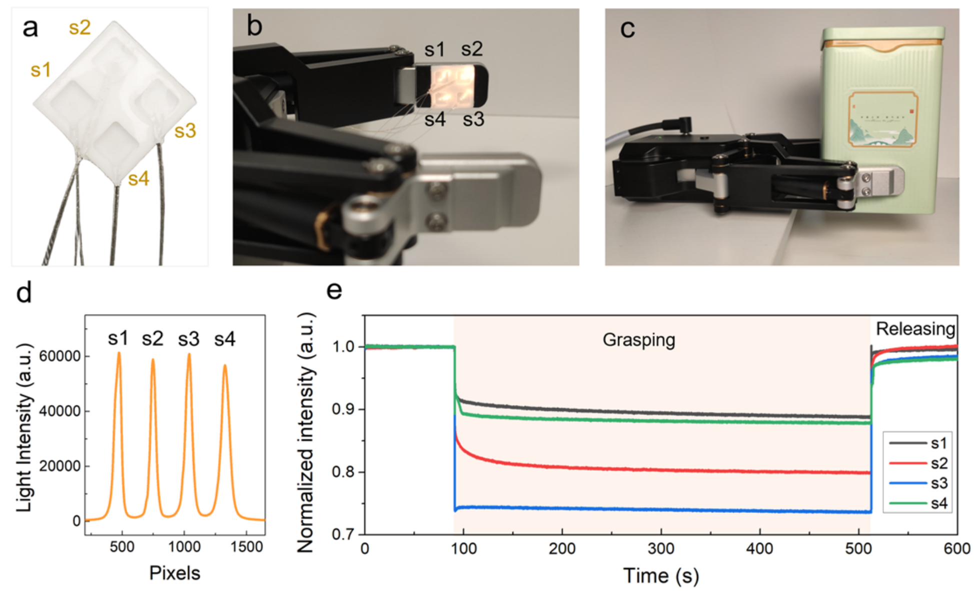

Fig. 7. (a) Photograph of the tactile sensor array composed of coiled multimode POF. (b) The tactile sensor array is integrated into the finger of an adaptive robot gripper. (c) The tactile sensor array is used to grasp an iron crate using the adaptive robot gripper. (d) Optical intensity of the four channels of the tactile sensor array acquired by a linear CCD array. (e) Response signals of the tactile sensor array during the during the seizing and releasing of an iron box.

Subsequently, we controlled the gripper, equipped with an integrated sensor array, to grab an iron box characterized by a modest mass and somewhat deformable configuration, as seen in Fig. 7(c). The gripper gradually closes, secures the box for a duration, then opens and releases it. The real-time optical intensity output from the four sensor units is obtained using a linear CCD array with a capture rate of 50 Hz. Figure 7(d) illustrates that the output optical signal of each tactile sensing unit has a unique peak. Figure 7(e) illustrates the recorded intensity fluctuation of the peak values for each tactile sensing unit during the grabbing and release of the iron box. All four tactile sensors registered the contact force as the claw grasped the box. The four sensing units exhibit varying responses throughout the operation, showing disparate contact forces at the surface of each sensing unit. The disparity in signals among the sensors can be attributed to the unique surface geometries of the iron box. This example illustrates that the suggested tactile sensor possesses significant application and practicality.

4. Conclusions

This work introduces a tactile sensor concept utilizing coiled multimode POF, readily sourced from commercial POF through a four-step manufacturing procedure. The coiled fiber functions as a force transducer through bending-induced loss. Upon exposure to external stress, the fiber coil undergoes deformation, resulting in a decreased bending radius and an escalation in bending loss. Experimental findings indicate that sensitivity and dynamic range may be modified by altering the number of coils. A resolution of 0.024 N and a dynamic range of 0-10 N for normal force detection were attained using a coiled POF with a coil diameter of 1.125 mm and coil quantity of 8.5. Ultimately, we integrated a coiled fiber tactile sensor array onto the finger of a robot manipulator to enhance grasping capabilities. Compared to current fiber optic tactile sensing technologies, our sensor has tremendous design freedom and outstanding resilience; additionally, it allows for mass production, implying significant promise for practical applications.

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Disclosures. The authors declare no conflict of interests

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. R. S. Dahiya, G. Metta, M. Valle, *et al.*, "Tactile Sensing—From Humans to Humanoids," IEEE Trans. Robot. **26**(1), 1–20 (2010).
2. Y. Li, P. Wang, C. Meng, *et al.*, "A brief review of miniature flexible and soft tactile sensors for interventional catheter applications," Soft Sci. **2**, 6 (2022).
3. M. Qian, Y. Yu, N. Ren, *et al.*, "Sliding sensor using fiber Bragg grating for mechanical fingers," Opt. Express **26**(1), 254 (2018).
4. L. Xu, N. Liu, J. Ge, *et al.*, "Stretchable fiber-Bragg-grating-based sensor," Opt. Lett. **43**(11), 2503 (2018).
5. L. Massari, G. Fransvea, J. D'Abbraccio, *et al.*, "Functional mimicry of Ruffini receptors with fibre Bragg gratings and deep neural networks enables a bio-inspired large-area tactile-sensitive skin," Soft Sci. **4**(5), 425–435 (2022).
6. K. Jin, Z. Li, P. Nan, *et al.*, "Three-dimensional force-tactile sensors based on embedded fiber Bragg gratings in anisotropic materials," Opt. Lett. **48**(9), 2269 (2023).
7. Z. Chen, B. Dong, Q. Shao, *et al.*, "Flexible Arc-Shaped Micro-Fiber Bragg Grating Array Three-Dimensional Tactile Sensor for Fingertip Signals Detection and Human Pulse Monitoring," ACS Appl. Mater. Interfaces **16**(32), 42986–42994 (2024).
8. T. Xu, L. Li, Y. Wang, *et al.*, "Highly sensitive soft optical fiber tactile sensor," Opt. Express **30**(19), 34064 (2022).
9. J. Weng, Y. Yu, J. Zhang, *et al.*, "A Biomimetic Optical Skin for Multimodal Tactile Perception Based on Optical Microfiber Coupler Neuron," J. Lightwave Technol. **41**(6), 1874–1883 (2023).
10. L. Li, T. Xu, Q. Ma, *et al.*, "Ultrasensitive measurement of tactile force based on a PDMS-embedded microfiber Mach-Zehnder interferometer," Opt. Express **32**(3), 3251 (2024).
11. Q. Wang, B. Yan, M. Wang, *et al.*, "The Tactile Force Sensing of the Gripper Based on the Mode Interference Fiber Sensor," IEEE Sens. J. **24**(19), 29716–29722 (2024).
12. Z. Ding and Z. Zhang, "2D tactile sensor based on multimode interference and deep learning," Opt. Laser Technol. **136**, 106760 (2021).
13. C. Jiang, Z. Zhang, J. Pan, *et al.*, "Finger-Skin-Inspired Flexible Optical Sensor for Force Sensing and Slip Detection in Robotic Grasping," Adv. Mater. Technol. **6**(10), 2100285 (2021).
14. W. Yu, N. Yao, J. Pan, *et al.*, "Highly sensitive and fast response strain sensor based on evanescently coupled micro/nanofibers," Opto-Electron. Adv. **5**(9), 210101 (2022).
15. Y. Wang, C. Jiang, T. Dong, *et al.*, "Flexible Micro-Nano Fiber Sensors for Tactile Sensing," IEEE Sens. J. **24**(4), 4458–4463 (2024).
16. L. Zhang, Y. Zhen, and L. Tong, "Optical micro/nanofiber enabled tactile sensors and soft actuators: A review," Opto-Electron. Sci. **3**(8), 240005 (2024).
17. H. Liu, X. Song, X. Wang, *et al.*, "Optical Microfibers for Sensing Proximity and Contact in Human–Machine Interfaces," ACS Appl. Mater. Interfaces **14**(12), 14447–14454 (2022).
18. Y. Tang, L. Yu, J. Pan, *et al.*, "Optical Nanofiber Skins for Multifunctional Humanoid Tactility," Adv. Intell. Syst. **5**(2), 2200203 (2023).
19. Y. Tang, H. Liu, J. Pan, *et al.*, "Optical Micro/Nanofiber-Enabled Compact Tactile Sensor for Hardness Discrimination," ACS Appl. Mater. Interfaces. **13**(3), 4560–4566 (2021).
20. J. h. Li, J. h. Chen, and F. Xu, "Sensitive and Wearable Optical Microfiber Sensor for Human Health Monitoring," Adv. Mater. Technol. **3**(12), 1800296 (2018).
21. H. Zhao, K. O'Brien, S. Li, *et al.*, "Optoelectronically innervated soft prosthetic hand via stretchable optical waveguides," Sci. Robot. **1**(1), eaai7529 (2016).
22. H. Bai, S. Li, J. Barreiros, *et al.*, "Stretchable distributed fiber-optic sensors," Science **370**(6518), 848–852 (2020).
23. J. Guo, X. Liu, N. Jiang, *et al.*, "Highly Stretchable, Strain Sensing Hydrogel Optical Fibers," Adv. Mater. **28**(46), 10244 (2016).
24. J. Pan, Q. Wang, S. Gao, *et al.*, "Knot-inspired optical sensors for slip detection and friction measurement in dexterous robotic manipulation," Opto-Electron. Adv. **6**(10), 230076 (2023).