



Elastic and Stretchable Functional Fibers: A Review of Materials, Fabrication Methods, and Applications

Mengxiao Chen¹ · Zhe Wang¹ · Kaiwei Li² · Xiandi Wang³ · Lei Wei^{1,4}

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Abstract

Elastic and stretchable functional fibers have drawn attentions from wide research field because of their unique advantages including high dynamic bending elasticity, stretchability and high mechanic strength. Lots of efforts have been made to find promising soft materials and improve the processing methods to fabricate the elastomer fibers with controllable fiber geometries and designable functionalities. Significant progress has been made and various interdisciplinary applications have been demonstrated based on their unique mechanical performance. A series of remarkable applications, involving biomedicine, optics, electronics, human machine interfaces etc., have been successfully achieved. Here, we summarize main processing methods to fabricate soft and stretchable functional fibers using different types of elastic materials, which are either widely used or specifically developed. We also introduce some representative applications of multifunctional elastic fibers to reveal this promising research area. All these reported applications indicate that the fast innovated interdisciplinary area is of great potential and inspire more remarkable ideas in fiber sensing, soft electronics, functional fiber integration and other related research fields.

Keywords Elastic fibers · Stretchable fibers · Fiber sensing · Multifunctional fibers

Mengxiao Chen and Zhe Wang have contributed equally to the work.

✉ Xiandi Wang
xiandiwang@zju.edu.cn

✉ Lei Wei
wei.lei@ntu.edu.sg

¹ School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

² Institute of Photonics Technology, Jinan University, Guangzhou 511443, China

³ Department of Biomedical Engineering, Key Laboratory for Biomedical Engineering of Ministry of Education, Zhejiang Provincial Key Laboratory of Cardio-Cerebral Vascular Detection Technology and Medicinal Effectiveness Appraisal, Zhejiang University, Hangzhou 310027, China

⁴ CINTRA CNRS/NTU/THALES, UMI3288, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553, Singapore

Introduction

Fiber technologies originated from ancient spinning techniques have been exploited into a wide range of application fields with the fast development of the material industry and modern processing technologies [1, 2]. The accessible materials are no longer limited to natural plants and animal furs, but further extended to glasses [3], semiconductors [4], carbon materials [5], non-stretchable polymers, soft polymers and abundant functional materials [6]. Various fabrication methods have also been developed such as thermal drawing, casting, molding, extrusion, printing and so on [7, 8]. More importantly, they have enabled a wealth of functionalities beyond aesthetics and warmth. For example, optical telecommunication, optical sensing [9], neural interface [10], thermal detection, and acoustic emission have all been achieved [11–13]. Specifically some milestones in carbon fibers have been achieved for aerospace, civil engineering, military, and sports due to their outstanding properties in stiffness, low weight, high chemical resistance, low thermal expansion etc. [14, 15]; mass production of polymer fibers and tubes (e.g. polytetrafluoroethylene (PTFE) fibers, silicone fibers) have been realized for industry use and medical

applications; and multi-material and multi-functional fibers have been demonstrated as high efficiency fiber energy storage units [16–18], luminescent fibers, photo detecting fibers [19], and electronic fibers [20]. Recently, polymers become more frequently used which can be processed under low temperature and they possess higher flexibility and better machinability, making them compatible with different functional materials and fiber architectures. Over the past few years, numerous non-stretchable polymer fibers (e.g., polycarbonates (PC) and polystyrene (PS)) have been demonstrated for applications in electronics [21, 22], energy conversion [23, 24], and biomedicine, etc. These various applications reveal the bright future of the fiber technology towards human–machine interface [25, 26]. Although these various fiber materials and fiber fabrication methods have benefited human life in numerous aspects, the limitations of these fibers still exist in soft and stretchable applications, such as conformal sensing, soft robotics, and textiles. Therefore, there is a rising demand for elastic and stretchable functional fibers because of their unique mechanical performance. Lots of efforts have been made to find promising soft materials and improve the processing methods to fabricate elastomer fibers with controllable fiber geometries and designable functionalities [27, 28].

Researchers have made significant progress in elastic and stretchable fibers and demonstrated various interdisciplinary applications based on their unique advantages including high dynamic bending elasticity, stretchability and high mechanic strength. Here, we summarize the main processing methods to fabricate soft and stretchable functional fibers using different types of elastic materials, which are either widely used or specifically developed. We also introduce some representative applications of multifunctional elastic fibers to

reveal this promising research area and inspire more remarkable ideas in fiber sensing, soft electronics, functional fiber integration and other related research fields. The remaining challenges and potential solutions toward advanced elastic and stretchable functional fibers are discussed in the end to provide some practical insights and viewpoints.

Materials and Fabrication Methods

Different from the conventionally used non-stretchable polymer materials such as PC and PS, elastomers offer superior conformability with the soft human skin and other irregular shaped surfaces due to their excellent stretchability and softness. The elastomer materials should be chosen according to fabrication methods and applications. For example, optical transparency and refractive index of the elastomers would be the most important property for waveguide fibers; thermoset elastomer such as polydimethylsiloxane (PDMS) is not feasible for long-term heating processing like thermal extrusion and thermal injection. Table 1 summarizes some representative polymeric materials, and feasible strategies for elastic fiber fabrication together with their mechanical properties (Elongation at break/stiffness).

In general, thermoset elastomers should be shaped to fiber before crosslinking and solidity. Once the thermosets crosslinked, it would be difficult to dissolve and soften. While thermoplastic elastomers (TPEs) are easily dissolved in solvents or melted. And they could be thermally processed via various methods, including thermal injection and thermal drawing. Hydrogels are formed by a network of cross-linked polymer chains that are hydrophilic. Sometimes they are found as a colloidal gel dispersed in water. The mechanical

Table 1 Typical materials used to fabricate elastic and stretchable fibers

Material	Fabrication methods	Elongation at break/stiffness	References
Thermosets			
Polydimethylsiloxane (PDMS)	Molding, coating,	80–231%	[39–44]
Epoxy	Printing		[45]
Hydrogel			
Poly(ethylene glycol) diacrylate (PEGDA)/alginate	Molding, coating	700%	[46, 47]
PEGDA-poly acrylamide (PAAm)/alginate		75%	[48]
TPE			
Styrene-ethylene-butylene-styrene (SEBS)	Molding, coating, thermal	100–700%	[30, 35, 49]
Cyclic olefin copolymer elastomer (COCE)	drawing, extrusion	230%	[50]
Biodegradable			
Agarose/Gelatin	Thermal drawing, molding,	300%	[51–53]
Poly(octamethylene maleate citrate) (POMC)/ poly(octamethylene citrate) (POC)	coating, extrusion	58%	[54]
Polylactic acid (PLA)/poly (lactic-co-glycolic) (PLGA)		1.94 kPa/2.4 × 10 ⁵ N/m	[55, 56]
Silk		> 400%	[57–60]

properties of hydrogels could be modulated by modifying the polymer concentration of a hydrogel and the crosslinking concentration. And their rubber elasticity and viscoelasticity make them appealing for many biomedical applications, which have been widely investigated. The last one is biodegradable materials based on naturally derived polymers such as agarose and cellulose, and synthetic degradable polymers such as modified polylactic acid (PLA), and poly (lactic-co-glycolic) (PLGA). These biodegradable polymers could be absorbed by the human body after degrading, showing great potential in biomedical applications (Fig. 1).

Starting from thermally drawing, a traditional fiber fabrication process [61], we introduce some feasible fabrication methods for elastic and stretchable materials. Figure 2a illustrates some typical steps to make a preform before being drawn into fibers [35, 37, 52]. The main purpose is to shape the materials as designed. Some of the steps can be omitted and adjusted depending on the requirements. For example, if the raw material is SEBS pellets and we need a SEBS round rod, it can also be realized by heating the pellets and injecting them into a round tubular mold followed by cooling. When preform preparation is completed, it is then placed on

the thermal drawing tower (Fig. 2b). And the clamp would draw it into thin fibers after the preform is heated to the processing temperature. Figure 2c shows some cross sections of elastic fibers fabricated via thermally drawing, indicating that customized structures can be achieved to meet different function needs.

Different from thermal drawing, 3D printing is a newly developed technology in recent years [62]. This is a three-dimensional layer-by-layer fabrication approach, allowing various materials to be precisely printed, including metals, ceramics, thermoplastic polymers and other polymers which could be cured under stimuli. As a result, 3D printing has become a versatile option to manufacture elastic fibers. Y. Tong et al. developed a 3D-printed elastomeric metal-core silicone-copper (Cu) (cladding-core) fiber, and worked as triboelectric nanogenerator (TENG) (Fig. 3a) [31]. Besides elastic fiber, 3D printing can also be used to manufacture assorted elastic subassemblies to develop a fully functional elastic system. P. Xu et al. developed optical lace (OL) for synthetic afferent neural networks [32]. They introduced a platform as OL for creating arbitrary 3D grids of soft, stretchable light guides for spatially continuous deformation

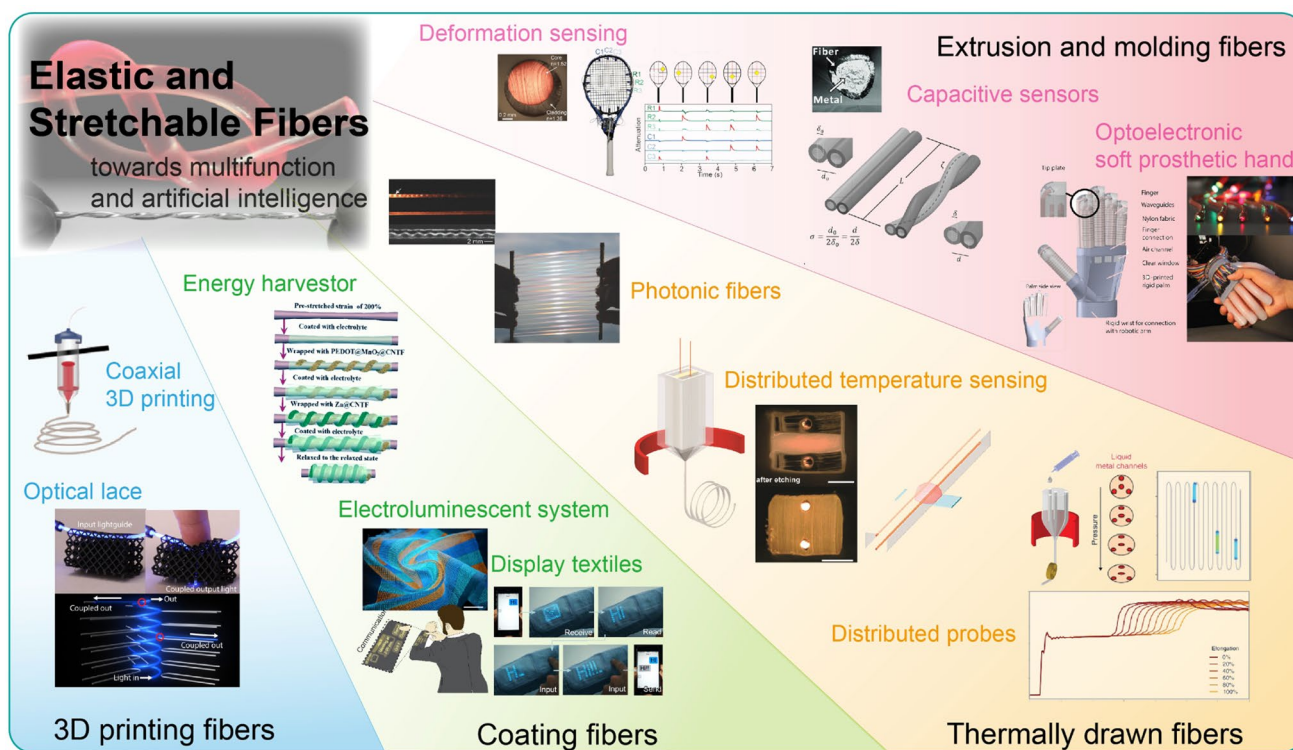


Fig. 1 Schematic of main fabrication methods and typical application achievements of elastic and stretchable fibers. Reproduced with permission [29]. Copyright 2018, Wiley–VCH; Reproduced with permission [30]. Copyright 2017, Wiley–VCH. Reproduced with permission [31]. Copyright 2020, Elsevier; Reproduced with permission [32]. Copyright 2019, AAAS; Reproduced with permission [33]. Copyright 2019, Elsevier; Reproduced under the terms of the

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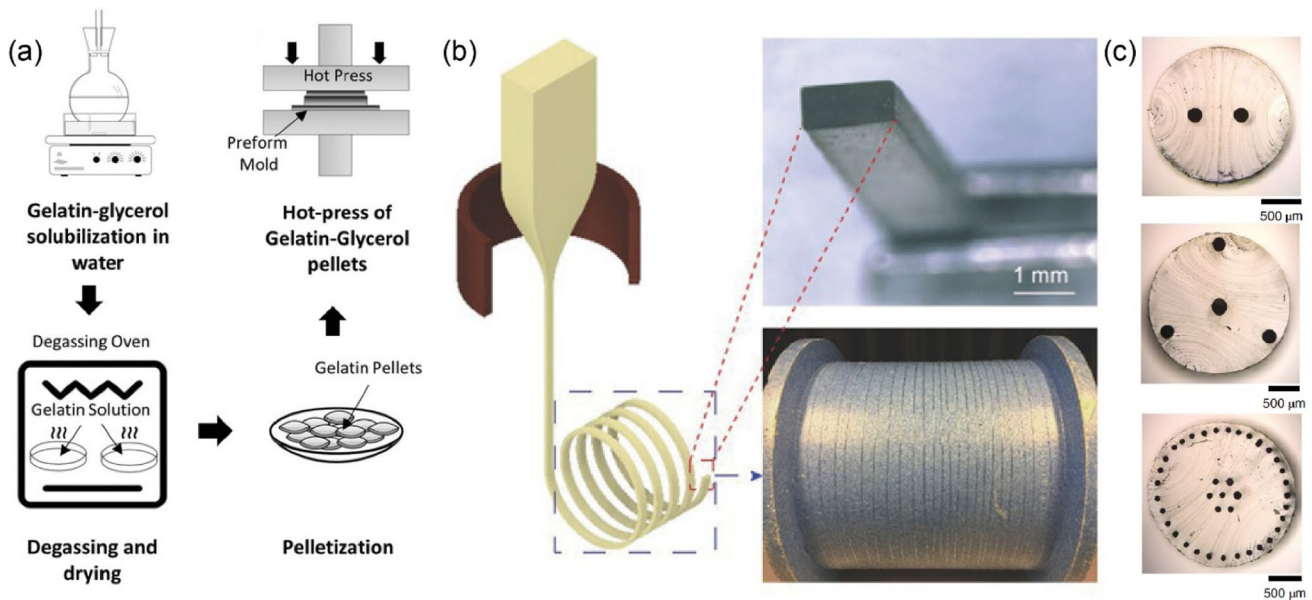


Fig. 2 Thermally drawn fibers. **a** Typical procedures to prepare preform. Some of them can be omitted depending on required material forms. Reproduced with permission [52]. Copyright 2019, Wiley–VCH. **b** Schematic to show how the preform is drawn into thin fibers

through the heating furnace. Reproduced with permission [35]. Copyright 2018, Wiley–VCH. **c** Cross section images of some thermally drawn elastic fibers with conductive cores. Reproduced with permission [37]. Copyright 2020, Springer Nature

sensing (Fig. 3a). This 3D sensory array provided functions similar to those of the afferent neural network in organisms. These light guide networks were distributed throughout the volume of a 3D-printed soft scaffold. Another fabrication method is a rotation-translation method for preparing the elastic conducting fiber. Z. Yang et al. developed a stretchable fiber-shaped dye-sensitized solar cell (DSSC) using this method [63–65]. As shown in Fig. 3b, two ends of the elastic fiber (e.g. rubber fiber) were attached to two motors. Then a continuous multi-walled carbon nanotubes (MWCNT) sheet fixed on a precisely motorized translation stage was drawn onto the elastic fiber with an angle. By adjusting the rotary speeds of the two motors and the moving speed of the translation stage, the MWCNT sheet was bundled onto the elastic fiber successfully as designed. The bounding force between the MWCNTs and the fiber surface was Van der Waals forces. Figure 3c illustrates another commonly used method to fabricate elastic fiber structures [66]. Cladding layer was coated on fiber core through dip- and spin-coating. The cladding layer was then cured by heating. Other coating methods like dry-coating was also used to fabricate the active enzyme layer-coated electrode of the stretchable bio-fuel cell fiber (Fig. 3d) [67].

Other elastic fiber fabrication methods are illustrated in Fig. 4. Figure 4a is a one-step co-extrusion fabrication of a stretchable fiber which was developed from basic extrusion method compatible with thermoplastic materials [29]. A. Leber et al. reported a core-cladding optical fiber via co-extrusion with polystyrene-based polymer Star Clear 1044

(refractive index (RI), 1.52) and fluorinated polymer Daikin T-530 (RI, 1.36) as core and cladding respectively. It sustained 300% tensile strains reversibly. Molding is another frequently adopted method to fabricate elastic fibers. A. Yetisen et al. reported a hydrogel optical fiber through molding with post coating steps [48]. Figure 4b shows the schematic of the core fabrication process through tube molding. Monomer solution was injected into a poly(vinyl chloride) (PVC) tube that served as a mold. Then it was crosslinked by exposing to UV light. The hydrogel fiber core was ejected from the mold by applying water pressure. As reported by Y. Zhao et al. (Fig. 4c) [67], dry spinning is a more direct way to form fiber structures in one step. The spinning solution was extruded out from a needle directly into the air. Due to the rapid evaporation of tetrahydrofuran (THF), the stream of the solution was dried to form fiber directly in the air at room temperature, and the Au nanowires (NWs)/SEBS elastic fiber was thus produced. H. Zhao et al. reported a multi-molding method achieving a stretchable optical waveguide. As illustrated in Fig. 4d, a pre-elastomer for the cladding was poured into the mold and demolded after curing [38]. Then the pre-elastomer of the core material was filled into the cladding. Finally, the pre-elastomer of the cladding was poured to enclose the core. At last, we introduce a strategy by rolling thin films to form fibers, which is not a scalable process but revealed an interesting performance in minimizing conductivity change when being stretched [68]. This strategy was reported by B. Zhang et al. as illustrated in Fig. 4e. They presented a cracking control strategy by simply rolling a facile PDMS thin film (10 μm thick) to prepare spiral structure

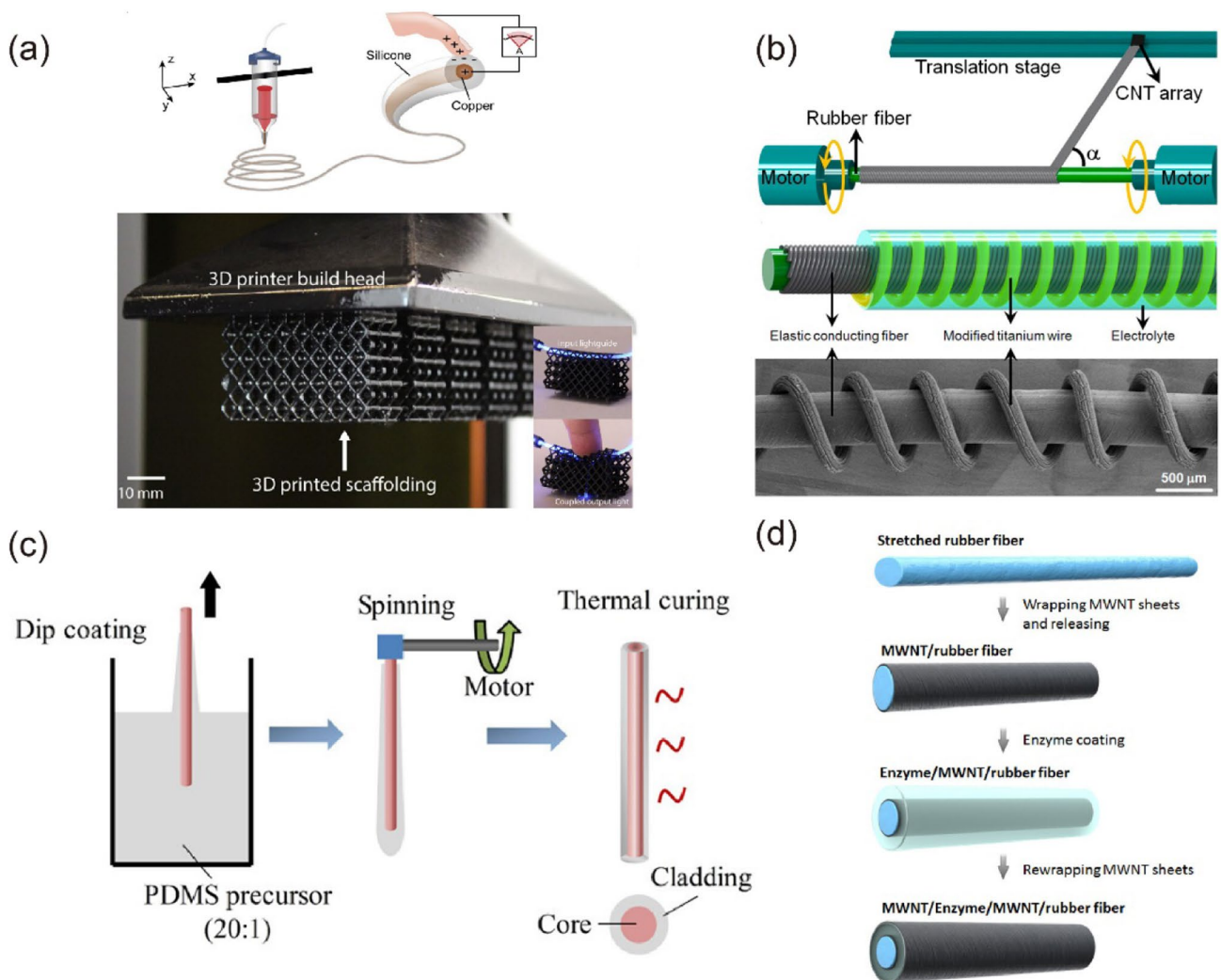


Fig. 3 **a** up: 3D-printed stretchable triboelectric nanogenerator fiber. Reproduced with permission [31]. Copyright 2020, Elsevier; Reproduced with permission. down: 3D-printed soft scaffolding with embedded channels for elastomeric light guide cores. Insets: LED illuminating the straight input core and light coupling to an output core when deformed. Reproduced with permission [32]. Copyright 2019, AAAS. **b** Schematic illustration about the rotation-translation method for preparing the elastic conducting fiber. SEM image of a

stretchable fiber-shaped DSSC. Reproduced with permission [63]. Copyright 2014, Wiley-VCH. **c** Fabrication steps of a PDMS cladding on a fiber through dip coating. Reproduced with permission [66]. Copyright 2019, American Chemical Society. **d** Fabrication process for stretchable biofuel cell fiber based on dry-coating. Reproduced with permission [67]. Copyright 2018, American Chemical Society

conductive fibers. There was an encapsulation effect to confine the elongation of cracks by reducing the stress concentration in the two ends of each crack. The crack size in fiber was reduced and more conductive pathways were preserved during stretching. Thus, the fiber kept a good conductivity under stretching.

Applications

Fibers have an intrinsic advantage for distanced information delivering and transferring. So, they can be naturally utilized for implantable biomedical sensing and monitoring

inside the body and tissues [69, 70]. Y. J. Heo et al. reported a long-term in vivo glucose monitoring using fluorescent hydrogel fibers. The polyethylene glycol (PEG)-bonded polyacrylamide (PAM) hydrogel fibers reduced inflammation and continuously responded to blood glucose concentration changes for up to 140 days [71]. Figure 5a–c shows the schematic and photographs to inject and remove the fluorescent hydrogel fiber, together with the continuous 140-day monitoring results. M. Choi et al. reported a step-index optical fiber made of biocompatible hydrogels to achieve a low-loss in vivo light guiding ($<0.42 \text{ dB cm}^{-1}$) over the entire visible spectrum. As indicated in Fig. 5d, two hydrogel fibers (one

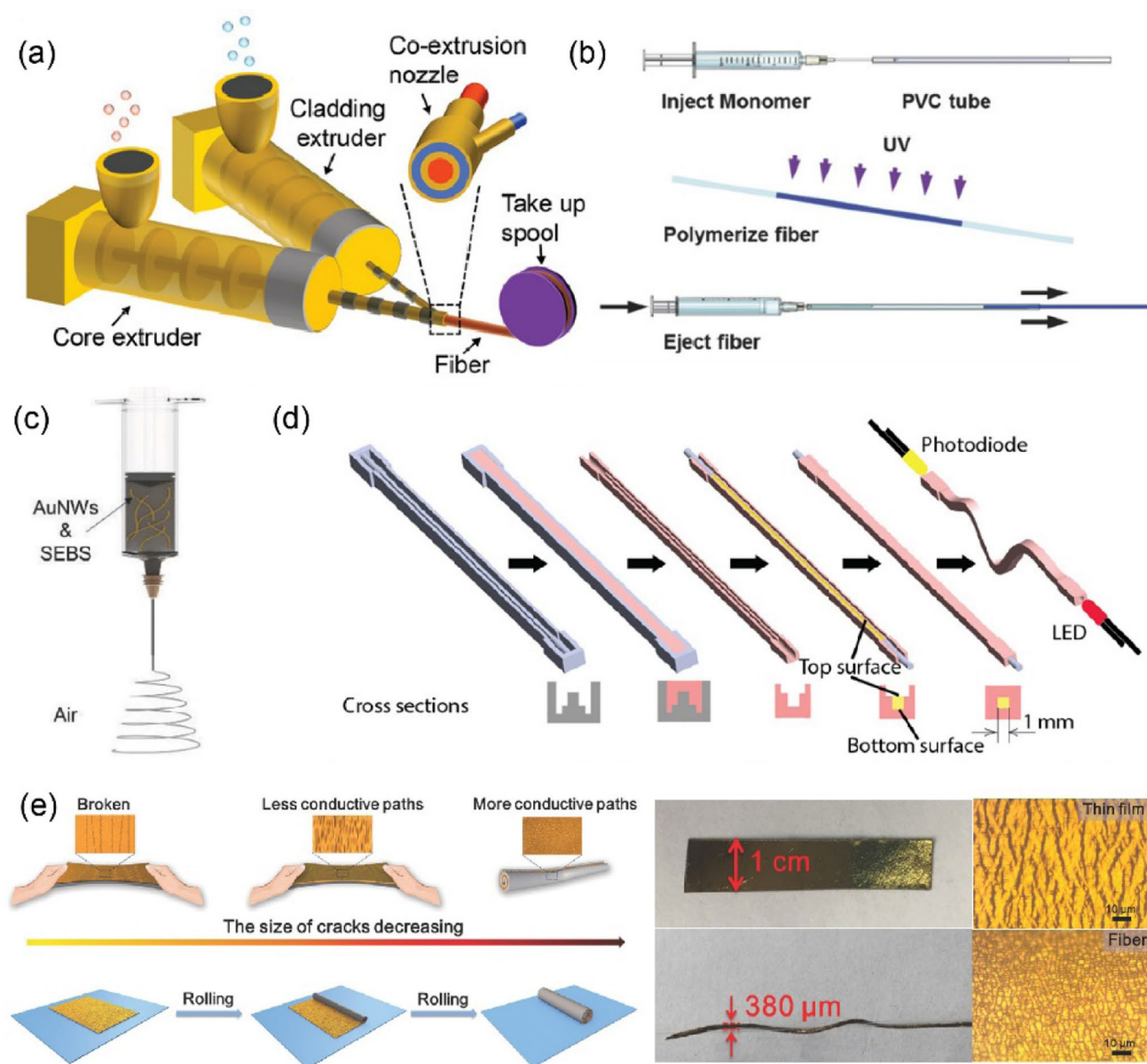


Fig. 4 **a** Schematic of the one-step coextrusion fabrication of a stretchable fiber. Reproduced with permission [29]. Copyright 2018, Wiley–VCH. **b** Steps to fabricate elastic fibers through a molding-ejecting method. Reproduced under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>) [48]. Copyright 2017, The Authors, published by Wiley–VCH. **c** Schematic illustration of the dry spinning process to fabricate AuNWs/SEBS fiber. Reproduced with permission [67].

Copyright 2018, American Chemical Society. **d** Steps for fabricating a waveguide through molding and the corresponding cross section for each step. Reproduced with permission [38]. Copyright 2016, AAAS. **e** Left: proposed principle of reducing the length and width of the cracks to achieve low resistance change while stretching. Right: Photograph of gold film on PDMS thin film and the prepared conductive fiber. The size of cracks on fiber was smaller than those on thin film. Reproduced with permission [68]. Copyright 2018, Wiley–VCH

for excitation and the other for collection) were implanted subcutaneously in an anesthetized mouse to measure the intrinsic optical absorption signal in response to oxygen/nitrogen ventilation [46]. C. Lu et al. developed a thermally drawn stretchable cyclic olefin copolymer elastomer (COCE) fiber coated with Ag nanowire (AgNW) mesh electrode layer to record spontaneous neural activity (Fig. 5e–l) [50].

Simultaneous stimulation and recording is demonstrated in transgenic mice expressing channelrhodopsin 2, where optical excitation evokes electromyographic (EMG) activity and hindlimb movement correlated to local field potentials measured in the spinal cord.

Besides *in vivo* applications, the elastomer materials can also be used in sensing and soft robotics. H. Zhao et al.

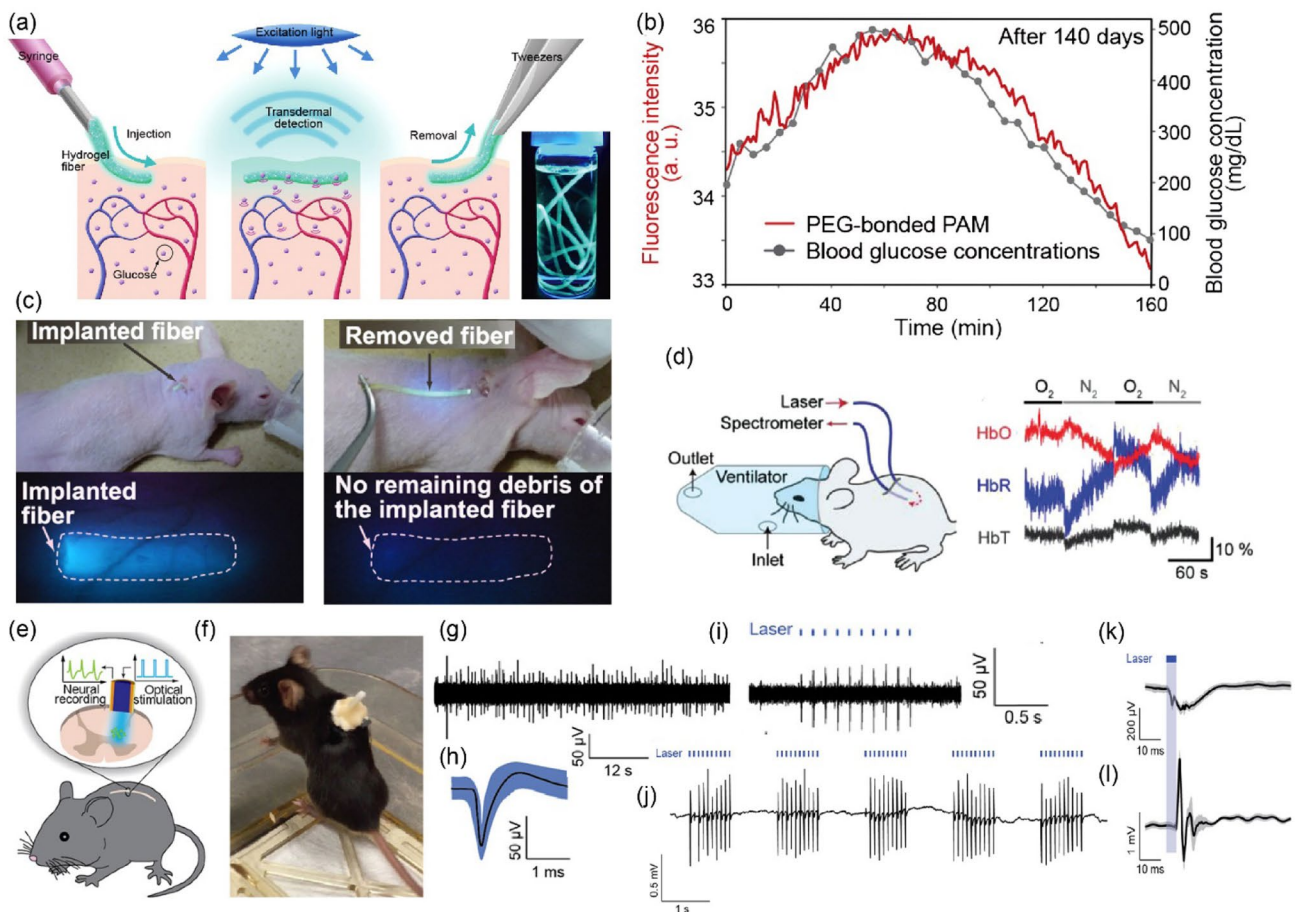
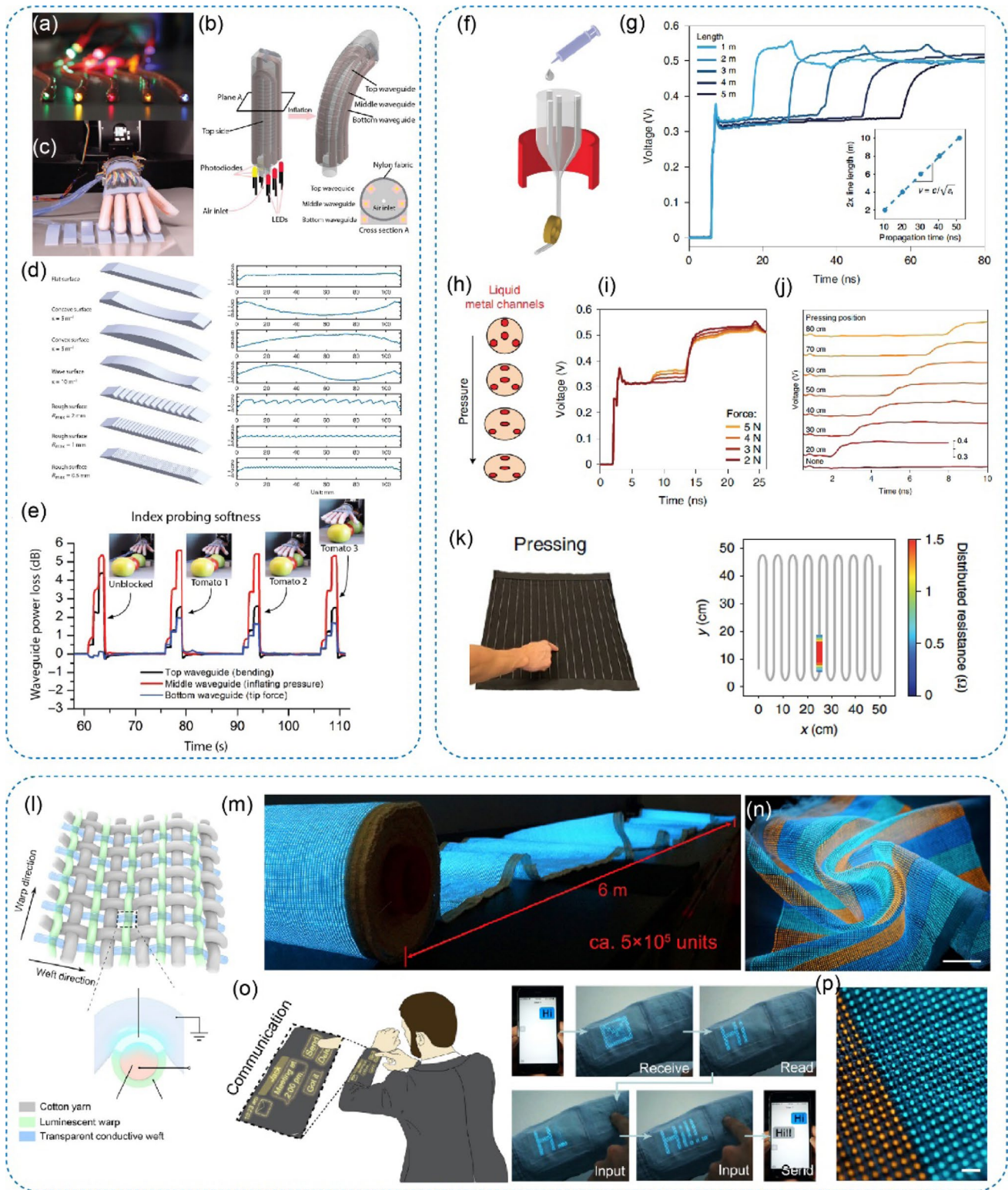


Fig. 5 Biomedical applications of elastic fibers for in vivo sensing and monitoring. **a** Schematic of the injected glucose-responsive fluorescent hydrogel fibers for long-term in vivo monitoring of blood glucose concentration. The inset is the fiber in glucose solution with excited UV light. **b** Implanted fluorescent fibers continuously corresponded to blood glucose concentration even after 140 days. **c** Removal of the implanted fiber from the mouse ear with no fiber debris. **a–c** Reproduced with permission [71]. Copyright 2011, National Academy of Sciences. **d** Two core-cladding hydrogel optical fibers implanted in mouse subcutaneous tissue to measure oxygenated and deoxygenated hemoglobin concentrations. Reproduced with permission [46]. Copyright 2015, Wiley–VCH. **e** Schematic to depict a fiber probe in a mouse spinal to cord optical stimulation and electrophysiological recording. **f** The mouse implanted with a neural fiber

probe. **g** Spontaneous activity recorded in acute conditions through the AgNW electrode layer on COCE core fibers. **h** Action potentials isolated from the recording in **(g)**. **i** Neural activity in spinal cord of a Thy1-ChR2-YFP mouse evoked by optical stimulation (wavelength 473 nm, 125 mW/mm², 5-ms pulse width, 10 Hz) delivered through the COCE fiber and recorded with the concentric AgNW mesh electrodes. **j** Electromyographic (EMG) evoked by the optical stimulation in **(i)**. **k** Optically evoked local field potentials recorded with AgNW mesh electrodes within COCE fiber. **l** An expanded view of the averaged EMG signal from **(j)**. Reproduced under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>) [50]. Copyright 2017, The Authors, AAAS

fabricated stretchable optical waveguides as photonic strain sensors based on several elastomer materials [38]. This waveguide was prepared by pouring the pre-elastomers successively into a mold to form a core/cladding structure. And the stretchable sensor was finished by fixing a light-emitting diode (LED) and a photodetector to the two ends of the optical waveguide, respectively (Fig. 6a). The core material used in this work was a polyurethane rubber with a refractive index of 1.461 and a propagation loss of 2 dB/cm at the wavelength of 860 nm, while a highly absorptive silicone composite (1500 dB/cm at the specified wavelength)

with a refractive index of 1.389 was selected as the cladding material. There are several reasons for choosing these two elastomers. Firstly, the large difference in refractive index between them ensures a large numerical aperture (0.45 at 860 nm) and acceptance angle ($\sim 26^\circ$), which makes it convenient for coupling the LED and the photodetector to the optical waveguide. Secondly, the large propagation loss of the core elastomer is beneficial for the sensing application: a small deformation of the waveguide will induce a relatively large change in the propagation loss, which is detectable by the low-cost photodiode and the current amplifying



circuit. Thirdly, the high-absorptive and low-index cladding elastomer could serve as both cladding layer to ensure total internal reflection and protection layer to preventing the light signal influenced by ambient light. Lastly, the mechanical properties such as elastic moduli and stretchabilities of two

elastomer materials are highly compliant, enabling the optical waveguide a stable performance under different deformation modes. After fabrication, the power loss of this optical waveguide was tested under elongation, bending, and local pressing, showing high linearity, repeatability, and precision

Fig. 6 Stretchable fiber applications in human–machine interfacing through optics, electronics, and optoelectronic systems. **a–e** Human–machine interface sensing system based on elastic waveguides. **a** Fabricated waveguides with a polyurethane rubber core and silicone cladding under assorted colored LEDs inserted from one end. **b** Schematic to illustrate the innervated finger with waveguide sensors. **c–d** Innervated prosthetic hand for texture detection. **e** Waveguide power loss during probing softness. Reproduced with permission [38]. Copyright 2016, AAAS. **f–k** Fiber electronics as distributed probes of multimodal deformations. **f** Schematic of the thermal drawing technique used to process liquid metal–thermoplastic elastomer constructs into long fibers acting as transmission lines. **g** Time-domain reflectometry waveforms observed for liquid metal triangular transmission lines of increasing lengths. **h** Schematic of the cross-sectional deformation mechanism of lines under increasing pressure. **i** Waveforms of 1 m–liquid metal–triangular lines loaded at 50 cm with an increasing pressing force. **j** Waveforms of load at different positions along liquid metal lines with equal force. **k** The distributed resistance upon finger pressing on the textile. Reproduced with permission [37]. Copyright 2020, Springer Nature. **l–p** Fiber photoelectronics as large-area display textiles integrated with functional systems. **l** Schematic showing the weave diagram of the display textile. Inset: an EL unit was formed at the contact area between luminescent warp and transparent conductive weft. **m–p** Photographs of the large scale display textile consisting of uniform EL units which could space at different distances by adjusting the weaving parameters. Scale bars: 2 cm in **(n)**, 2 mm in **(p)**. **o** Schematic and photographs to show that it worked as a communication platform to receive and send messages. Reproduced under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>) [34]. Copyright 2020, The Authors, under reviewed by Springer Nature

to these deformation modes. To reveal its potential in soft robotics, finger actuators were constructed. As shown in Fig. 6b, the bending behavior of the figure was controlled by the internal pressure in the air channel, and three waveguides were bent to U-shape and casted inside the finger. The top waveguide experienced the largest strain when the finger bends, i.e., the top waveguide was the most sensitive to the bending motion. The middle waveguide was located in the middle plane of the figure to monitor the internal pressure. And the bottom waveguide was placed at the neural bending plane and extended to the fingertip, aiming to detect the contact force during the touching behaviors. Thus, haptic sensations, including internal pressure, bending, and external force, could be achieved by monitoring the power loss information from the three waveguides. A soft prosthetic hand was further built by mounting the fingers on a 3D printed palm mounted on a robot arm as shown in Fig. 6c. Using the robotic arm, the hand can be guided to laterally scan the surfaces of different objects and generate the topographical information. As shown in Fig. 6d, the height profile of different surfaces could be reconstructed, showing its capability of detecting surface shape and roughness. Moreover, the softness of object detection could also be achieved by monitoring the bending state (top waveguide) and contact force (bottom waveguide). Furthermore, object recognition was demonstrated by combining shape and softness detection.

This soft prosthetic hand successfully recognized the ripe tomato, as shown in Fig. 6e, representing the great potential of elastomer materials in the field of soft robotics.

However, for most of the reported mechanical sensors, only one type of deformation and one point in space could be achieved by a single sensor [37]. Taking the optical waveguides introduced above as an example, a single waveguide could only detect one motion (stretching, bending, or single point pressing) at one time as the response signal is a scalar quantity (the optical power loss), in which the type of deformation type or location of pressure could not be distinguished. Although multifunctional sensing applications could be achieved by involving more sensors to form a sensing network (for example, by integrating more than ten waveguides into a prosthetic hand), the system complexity and the need of addressing all the sensors separately still greatly limits their sensing capabilities. To address these limitations, A. Leber et al. developed a soft and stretchable transmission line based on SEBS elastomer and liquid metal for detecting multimodal deformations simultaneously through interrogation by time-domain reflectometry [37]. The elastomer transmission line was fabricated by the thermal drawing technique. A SEBS preform with predesigned channels was used as shown in Fig. 6f, and the liquid metal was filled into the channels inside the preform followed by co-drawing with SEBS or injected into the microchannels in the drawn SEBS fiber to form the soft and stretchable transmission line. Owing to the good control over material and architecture achieved via the thermal drawing technique, the transmission line was uniform throughout its whole length and the configuration of the microchannels could be accurately arranged. The transmission lines with different lengths were interrogated with electrical time-domain reflectometry and the waveforms were obtained as shown in Fig. 6g. A signal with a step function was used in the measurement. The initial rise in the waveform represented the first incident of the signal and then propagation on the line. After a certain time, a full reflection was detected at the end of the open-circuit terminated line. Therefore, the length of the transmission line could be obtained by the propagation time and speed (light speed in the dielectric medium), which agreed well with the actual length (Inset of Fig. 6g. The flat signal between the first rise and full reflection indicated that the distributed resistance of the transmission line was very uniform because any change in distributed resistance could cause partial reflection, which was crucial for deformation sensing. As shown in Fig. 6h, when the transmission line was pressed, the liquid metal channels deformed accordingly, leading to an increase of distributed resistance at the pressing position. Figure 6i records the propagation signals under different pressing forces in the same position. An increased reflection was observed as the pressing force gets larger. Besides sensing the pressing force, the pressing

position was also be reflected in the propagation signal. As shown in Fig. 6j, the pressing position was distinguished by the time point of the partial reflection. Finally, an electronic textile was demonstrated based on a single transmission line (Fig. 6k). Both the pressing force and position were monitored and visualized simultaneously. This demonstration reveals the application prospect of this multimodal deformation sensor in wearable devices and robotic skins.

Through functionalizing the pre-elastomer, large-area display textile was achieved recently [34]. As sketched in Fig. 6l, ionic-liquid-doped polyurethane gel was employed to form the transparent conductive weft fibers and ZnS phosphor dispersed in an insulating polymer matrix (polyurethane) was coated on conductive yarns serving as luminescent warp fibers. A display textile was thus woven with microscale electroluminescent (EL) units at the weft-warp contact points. Figure 6m shows a 6-m-long display textile consisting of approximately 5×10^5 EL units. And multicolor soft display textile was fabricated by altering the EL units (Fig. 6n, p). This weaving strategy was proven to be general by integrating fibers with other electronic functions into the same textile. This integrated textile could also be used as a wearable communication tool and interact with a handphone supported by the keyboard and Bluetooth module (Fig. 6o). It reveals great potential in various areas including Internet of Things. And the ability of this approach for fabrication and integration of different electronic functions is expected to shape the next-generation electronics.

Conclusions and Outlook

Enabled by the traditional fiber manufacturing industry, elastic and stretchable fiber has been developed in both material exploration and fabrication approach innovation. A series of remarkable applications, involving biomedicine, optics, electronics, human machine interfaces etc., have been successfully achieved. All these reported applications (implantable in vivo biomedical sensing, innervated prosthetic robotic hand, distributed probes of multimodal deformations and large-area display textiles integrated with functional system) indicate that the fast innovated interdisciplinary area is of great potential. Nevertheless, the study of the material system of elastomer fibers is still at the initial stage, and there is broad space to be explored. Towards material innovation, extensive functional materials could be designed and synthesized to meet different requirements of various fabrication methods. For example, hydrogels which could maintain a proper viscosity for thermally drawing could then be developed by studying the chemical synthesis process. Hydrophilic and hydrophobic segments could be designed to the polymer chain structure to further form a stretchable hydrophilic or

hydrophobic fiber. Fibers with more functionalities could be expected through investigating the surface modification and functional structure design inside the fiber [72]. For example, recently a direct imprinting method was developed to print functional patterns on fiber surface [6]. And some metastructures could be introduced into the fiber to obtain special optical function. Thus, these special functionalities can be implemented to more application scenarios through the elastic fiber devices. And more integrated fiber systems consisting of signal sensing, information transferring, and human machine interaction could be developed to include more functions by engaging other research fields from integrated circuits, data analysis, and mechanical design [73] (e.g., triboelectric nanogenerator system based on elastic fibers [74, 75]). More inspiring elastic and stretchable fiber-based work can be expected resting at the cross-section of many disciplines ranging from soft electronics, multi-functional sensing, energy harvesting, data science, to scalable manufacturing.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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Mengxiao Chen received her B.S. degree in physics (2012) from Northeastern University and Ph. D. in physics (2017) from Beijing Institute of Nanoenergy and Nanosystems, CAS, China. She is currently a research fellow in Prof. Wei Lei's group in Nanyang Technological University. Her main research interests are novel self-powered systems and multifunctional electric and photoelectric devices, and is now focusing on soft material based devices and their applications.



Zhe Wang received B.S. (2013) in Physics and M.S. (2016) in Material Physics and Chemistry from Lanzhou University, China. Now he is a Ph.D. student in School of Electrical and Electronic Engineering at Nanyang Technological University, Singapore. His research mainly focuses on fiber-based devices.



Kaiwei Li received the B.E. degree in mechanical engineering from Jilin University, Changchun, China, in 2009, and the Ph. D. degree in mechanical engineering from the Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China in 2014. In 2015, he joined the Centre for Optical Fibre Technology, Nanyang Technological University, Singapore, as a Research Fellow. In 2019, he joined the Institute of Photonics Technology, Jinan

University, Guangzhou, China. His research interests include fiber-optic sensors and Multimaterial multifunctional fibers.



Leiwei is an Associate Professor at Nanyang Technological University in Singapore. He received the B.E. degree from Wuhan University of Technology in 2005; and the Ph.D. degree from Technical University of Denmark in 2011. Then he joined the Massachusetts Institute of Technology as a postdoctoral associate. In 2014, he joined the School of Electrical and Electronic Engineering at Nanyang Technological University in Singapore as a Nanyang Assistant Professor. In 2019, he was pro-

moted to Associate Professor with tenure. His main research interests are fiber-based devices, multi-functional fibers, bio-fiber interfaces, and in-fiber energy generation and storage.



Xiandi Wang received his PhD degree in condensed matter physics from the University of Chinese Academy of Sciences in 2016. He had been a postdoc fellow in Professor Zhong Lin Wang's group at National Center for Nanoscience and Technology. He is currently an associate professor principle investigator at Zhejiang University since 2020. His main research interests focus on the fields of piezo-phonic effect and triboelectric nanogenerator for fabricating novel flexible large-scale tactile

sensor matrix and stretchable electronics.