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An Electromagnetic Fiber Acoustic Transducer with Dual Modes of Loudspeaker and Microphone

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A flexible fiber acoustic transducer is created by designing a parallel configuration of a Rubidium iron boron (NdFeB) magnet fiber and an aluminum fiber. The former provides a stable magnet field, while the latter vibrates to phonate upon applying alternating current or generates alternating voltage in the sound field. This single device exhibits dual functions as a loudspeaker or a microphone. As a fiber loudspeaker, it can generate 40–60 dB of audible (20 Hz–20 kHz) and directional sounds which can be used for blind navigation and controllable sound field distribution. The fiber acoustic transducer functions as a microphone when external sound waves force the aluminum fiber to vibrate. After the fiber microphones are woven into several different positions of a piece of clothing, the sound source can be accurately located based on the time differences reaching different microphones. This wearable fiber acoustic transducer is promising to be used to quickly search people in trouble during emergency rescue activities such as earthquakes or fires.

1. Introduction

Sound is a significant tool for information transfer and human–machine interaction. The common single-element acoustic transducers (different from the transducer array) are point-sound sources with the radiated pattern of acoustic wave front resembling a spherical wave,[1,2] while the line-source loudspeaker is arousing growing research interests because of its well-behaved directivity, great sound quality, and high output power[3–5] recently. The linear sound source is typically realized by dozens of point-source loudspeakers arranged in a line array. To produce the linear sound source, the distance between two neighboring loudspeakers should be less than the half wavelength of the highest operating frequency, and the length of the line-source array should be larger than the half wavelength of the lowest operating frequency.[6] However, considering the opposite relationship between wavelength and frequency, it is challenging to achieve a linear sound source with a wide operating frequency range by the traditional design of loudspeaker with acoustic transducer arrays.[7]

On the other hand, with the rapid development of portable electronics, it is also significant to develop flexible acoustic transducers to meet specific applications.[8–13] Recently, some thin-film acoustic transducers have been proposed for wearable purposes but they only demonstrate limited flexibility and poor breathability, thus leading to a rapid performance degradation or even functional failure during practical applications.[14–19] Further, it is almost impossible to stably integrate them into smart textiles with various functional fiber as building units, which represents a new booming direction in portable and wearable electronics.[20–22] To the best of our knowledge, the functional fiber that can serve as an acoustic transducer remains unavailable yet. As a result, it is necessary to develop a novel flexible acoustic transducer based on creative device architecture and working principle.

Here, we demonstrate a fiber acoustic transducer by assembling an aluminum fiber on an NdFeB magnet fiber. Aluminum is selected as the functional part for its softness, light weight and thermal-stability, while NdFeB magnet fiber is employed due to its flexibility and typical magnetic properties. The resulting fiber acoustic transducer is highly flexible and can work stably even after bending for 1000 cycles. Besides, it can function with dual modes of loudspeaker and microphone. As a loudspeaker, aluminum fiber vibrates under ampere force[23] with the applied alternating current and generates 40–60 dB of audible sound (20 Hz–20 kHz). Due to the one-dimensional device configuration, the pressure field generated by the fiber loudspeaker is anisotropic, followed by the production of a directional sound and a controllable sound field distribution, which provides application possibilities for blind navigation. Reversely, the fiber acoustic transducer can also function as a microphone when the external sound waves force the aluminum fiber to vibrate. After several fiber microphones are woven into different positions of a textile, the sound source can

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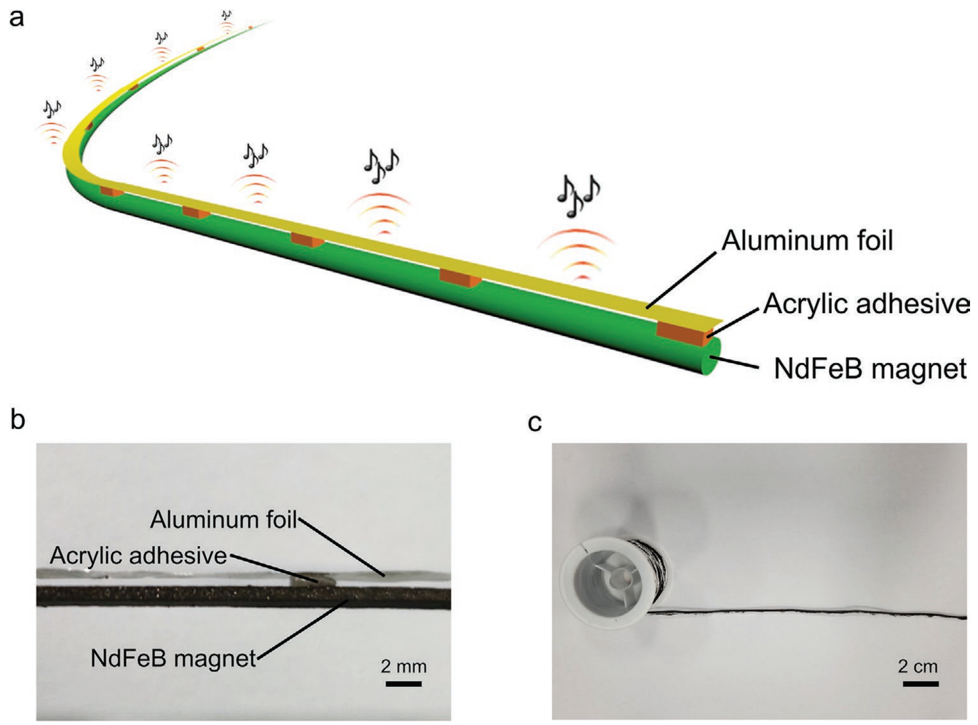

Figure 1. Structure of the fiber acoustic transducer. a) Schematic illustration. b) Photograph of fiber acoustic transducer comprising top aluminum foil, middle acrylic adhesive and bottom NdFeB magnet. c) A roll of fiber acoustic transducer.

be located according to the time differences reaching different fiber microphones of the sound,[24] which demonstrates significant application potentials in searching people struck in fires and earthquakes.

2. Results and Discussion

In a typical fabrication of fiber acoustic transducer, the NdFeB magnet was made into a square fiber, while aluminum foil was designed into a strip fiber. With the aluminum strip fiber parallelly attached onto the NdFeB magnet by interval acrylic adhesive columns, a fiber acoustic transducer was constructed (**Figure 1**a). Figure 1b demonstrates a typical photograph with the top aluminum fiber, the middle interval acrylic adhesive and the bottom NdFeB magnet. Further, the fiber acoustic transducer can be continuously fabricated by a home-made equipment (Figure S10 and Video S1, Supporting Information). Two rollers of aluminum fiber and NdFeB magnet fiber with acrylic adhesive spacer were compacted by a rubber roller and collected through another roller. Two spacing holes before and after the rubber roller were designed to position the aluminum and NdFeB magnet fibers, respectively. The gearbox would stabilize the load by the reduction gear when the electromotor was running. Figure 1c shows a roll of continuous fiber acoustic transducer fabricated by the home-made equipment.

We first investigated the performance of fiber acoustic transducer as a loudspeaker (**Figure 2**; Figures S1–S9, Supporting Information). The working principle of the fiber loudspeaker is the same as the dynamic electroacoustic transducer,[25,26] that is, the aluminum fiber in magnetic field vibrates driven by ampere force when an alternating current is applied (Figure 2a). The sound pressure level (SPL) can be easily controlled by adjusting the voltage applied to the electrodes (Figure S9, Supporting Information). The vibrating frequency of the aluminum fiber can be readily tuned by the frequency of applied alternating current. The vibration occurred at the two directions along the thickness and width based on the results of Free-space Single-point Laser Doppler Vibrometer (Figure S2, Supporting Information). The fiber loudspeaker can generate audible sounds between a frequency range of 20 Hz–20 kHz when a sinusoidal alternating voltage with a amplitude of 2 V is applied. An SPL range from 40 to 60 dB, corresponding to 2–20 mPa in sound pressure, can be achieved, which is comparable to the typical value of human voice (Figure 2b).[27] Note that the SPL was similar to the ambient noise when the alternating voltage was applied on an aluminum fiber without NdFeB magnet fiber, under which circumstance the thermoacoustic effect did not cause any obvious vibration of air molecules, indicating the thermoacoustic effect was negligible.

The acoustic performance of the fiber loudspeaker is greatly influenced by the size of aluminum fiber. For instance, the SPL increased with decreasing thickness of aluminum fiber because less mass led to larger vibration amplitude (Figure 2c), while SPL decreased with increasing width of aluminum fiber (Figure 2e). If not specified, the aluminum fiber with a 10 µm in thickness and a 1 mm in width was selected, and the distance between two neighboring acrylic adhesive columns was optimized to 25 mm. The SPL reached its maximal value when the aluminum foil was fixed on the two poles of NdFeB magnet fiber because the magnetic field decreased from the two poles (0° and 180°) to the equator (90°) (Figure 2d).[28]

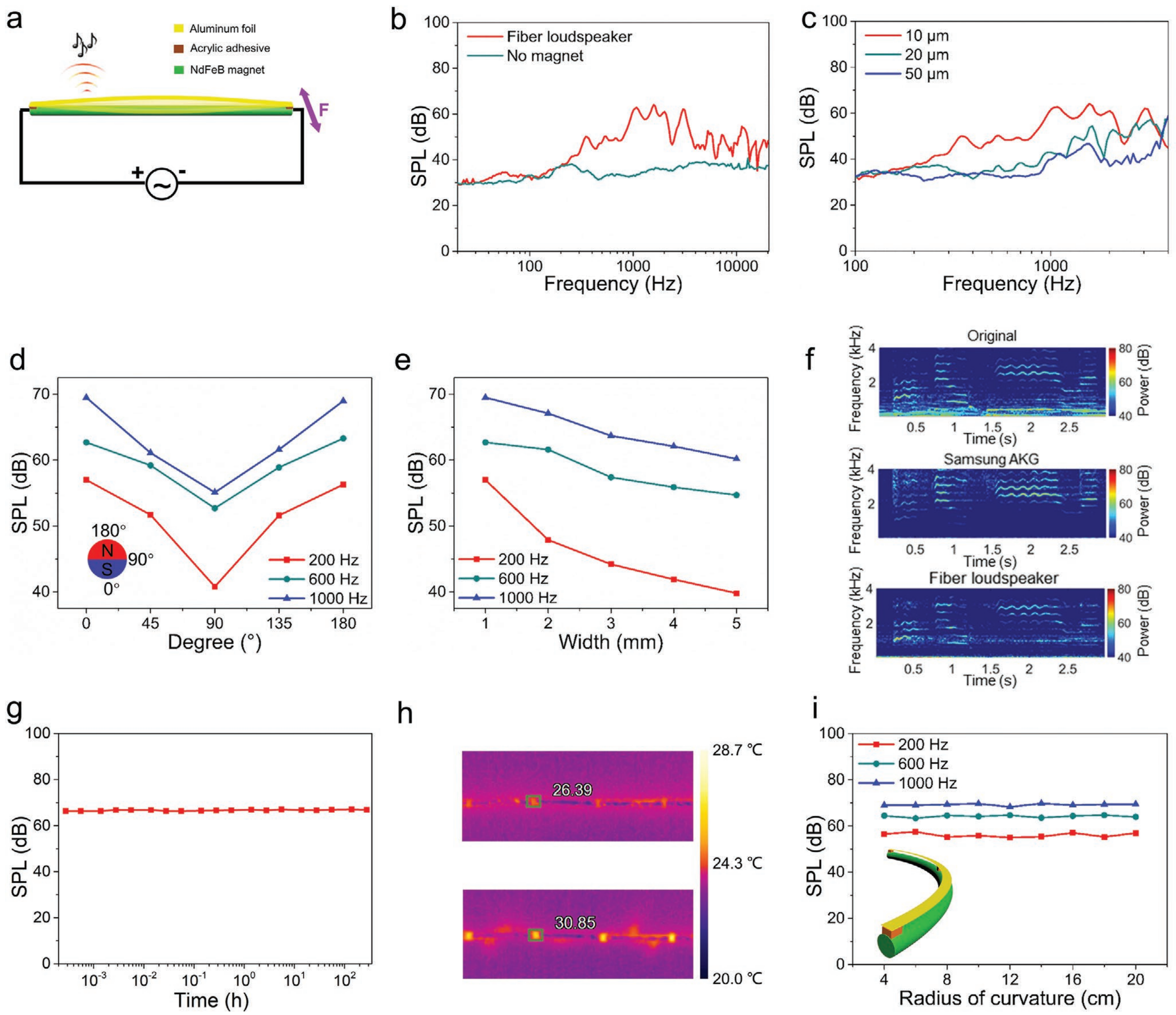

Figure 2. Acoustic performances of the fiber acoustic transducer as a loudspeaker. a) Schematic diagram of the working principle. b,c) Frequency response curves of the fiber loudspeakers with and without NdFeB magnet and using aluminum foils with different thicknesses, respectively. d,e) SPL variations with the position (inset, cross-sectional scheme of the NdFeB magnet fiber) and the width of aluminum foil fiber, respectively. f) Time-frequency analysis of the original audio (the audio output by Samsung AKG earphone and the audio output by the fiber loudspeaker). g) SPL variations with time for a duration of 10^6 s (about 277 h). h) Infrared thermography images of the fiber loudspeaker before and after working for 3 h. i) SPL variations with different curvature radii.

The time-frequency analysis[29] result indicated the fiber loudspeaker could play the original audio and reappear its abundant harmonic frequency contents (Figure 2f). No obvious second harmonic frequency was observed, indicating the thermoacoustic phenomena was negligible.[14] The tone quality of the fiber loudspeaker was similar to the commercial counterparts like Samsung AKG earphone (Audio S1, Supporting Information).[30] However, when the aluminum fiber was replaced with other metals such as silver, copper, titanium and zinc, their time-frequency results showed a lack of harmonic frequency contents (Figure S3, Supporting Information). Aluminum fiber presents a much better tone quality than other metals because its lower density allows for a larger vibration amplitude and a higher SPL under the same current condition. When the interval distance between the acrylic adhesive columns was changed, the SPL decreased below 11 mm and the noise appeared above 50 mm (Figure S4, Supporting Information). If the interval distance between the acrylic adhesive columns was reduced to 11 mm, the decreasing SPL also led to low signal to noise ratio because lower distance caused smaller vibration amplitude. Moreover, when the interval distance was set between 50 and 100 mm, high frequency contents were missing and the noise appeared at the low frequency region due to the ultraharmonics distortion, thus resulting in undesirable signal to noise ratio. Longer interval distance led to a lower central frequency of the fiber loudspeaker (Figure S5, Supporting Information), namely a worse frequency response at high frequency regions.

The fiber loudspeaker could stably work for a long duration of 10^6 s (about 277 h) without any obvious recession when a voltage of 2 V and a frequency of 1000 Hz were used (Figure 2g). With a magnetic field intensity of NdFeB fiber of 0.6 T, the ampere force (F) applied on the aluminum fiber is calculated as 15 mN based on Equation (1)[31]

$$F = \int I \mathrm{d}\boldsymbol{l} \times \boldsymbol{B} \tag{1}$$

where $\boldsymbol{l}$ is a vector whose magnitude is the length of the aluminum fiber (dl is an infinitesimal segment of aluminum fiber), $\boldsymbol{B}$ is the intensity of the magnetic field, and I is the alternating current. The cross-sectional area of aluminum fiber is 0.01 mm^2, so the stress of vibration is calculated as 1.5 MPa, which is an order of magnitude lower than the fatigue limit[32] of a metal. Moreover, the infrared thermography revealed a temperature variation of less than 5 °C before and after operation (Figure 2h), indicating a necessary thermal stability for wearable applications.

The fiber loudspeaker could stably work to withstand various deformations like bending and twisting. For instance, the SPL was well maintained after the fiber loudspeaker was bent with different curvature radii (Figure 2i; Figure S6, Supporting Information), and no obvious performance decline occurred after 1000 bending cycles (Figure S7, Supporting Information). It also showed stable performance when it was twisted with various pitches (Figure S8, Supporting Information). Moreover, when the fiber loudspeaker was woven into a textile, it also generated stable sounds when the textile was bent (Video S2, Supporting Information), indicating a good stability to satisfy the requirements of wearable electronics and smart textiles.

The fiber loudspeaker is also promising to achieve adjustable directional sound. To demonstrate this feature, a finite element analysis was conducted to simulate the propagation of the directional sound. To simulate the vibration of the loudspeaker with fixed points, a perpendicular velocity was given to the loudspeaker with a fixed point every 25 mm. For a straight fiber loudspeaker, the SPL in the radial direction was evidently larger than that along the axial direction (**Figure 3**a). Sound source array often show sidelobes which produces side effects on the directivity.[33] As a comparison, since the fiber loudspeaker can be viewed as an array with infinite number of dot-like sound sources, the sidelobes disappeared according to the simulation of the directivity of the line-sound source. It should be noted that the experiment data matched well with the simulated results (Figure 3b). For a straight fiber loudspeaker, the SPL along the radial direction was about 20 dB larger than that along axial direction, which was in accordance with the simulation of anisotropy of the fiber loudspeaker (Figure 3c). For a fiber loudspeaker in circular arc configuration with a radius of 640 mm, the center of the circle presented an SPL of 20 dB larger than the ambient area at common frequencies (Figure 3d; Figure S11, Supporting Information). This was caused by the interference enhancement at the circle center because of the equal distance from the center to each point on the fiber loudspeaker.[34] Experimentally, the SPL at the circle center was larger than the ambient area (Figure S12, Supporting Information), which also agreed well with the simulation results.

The directional sound is promising to be used to guide the blind towards their destinations (Figure 3e). For instance, in a typical scenario, when two blind men want to go to different destinations, the two fiber loudspeakers at the same broadcasting station can send two pieces of directional sounds to their respective locations, and then the two blind users at Location A and B could hear the respective orders (e.g., with corresponding frequencies of 1500 and 1000 Hz, respectively) without any disturbance of each other (Figure 3f). Furthermore, benefited from the high flexibility, it is expected that the curvature radius of the fiber loudspeaker can be readily tuned to adjust the focus point of the sound according to the movement of the blind people.

Reversibly, the fiber acoustic transducer can function as a microphone. The fluctuation of the air caused by the sound forced the aluminum foil to vibrate in magnetic field, which induced the generation of alternating voltage due to the electromagnetic effect[35] (**Figure 4**a). The time-frequency analysis shows that the frequency comments of the audio recorded by the fiber microphone was similar to that of original sound (Figure 4b). The power difference at some frequencies might originate from the frequency response variation of the fiber acoustic transducer in the broadband,[16,18] thus leading to higher sensitivity to the frequency components around central bandwidth than the others. The time-frequency analysis showing various frequency components also indicates the fiber microphone could record multiple sound sources with different frequencies. The individual components can be further extracted by using several microphones through an independent component analysis method.[38] As shown in the Audio S2 (Supporting Information), the actual recording performance can be intuitively experienced. Moreover, the fiber acoustic transducer possessed the ability to produce sound and receive its echo (Figure S14, Supporting Information), which is promising for location of sound source.

When flexible fiber microphones were woven into several different positions of a piece of clothing, an unknown sound source can be readily located by the fiber microphones based on the theory of multialteration[36] (Figure 4c). For instance, by using a typical signal processing method based on matching filter,[37] the distance differences between sound source and different microphones were calculated to determine the location with the known time delay and sound velocity (340 m s^{-1}) (Figure 4d,e; Note S13, Supporting Information). The measured location coordinate of the sound source was close to the actual one. The design provides significant applications for the emergence rescue activities (Figure 4f). Specifically, in disaster scenes like earthquake or fire where the view of the rescuer is possibly blocked, the rescuer can locate the sufferer accurately and efficiently with the aid of fiber microphones woven in the clothes, based on the time delay of fiber microphones to receive the sound of the sufferer (like shout for help).

3. Conclusion

In summary, we have, for the first time, produced a fiber acoustic transducer that works in dual modes of loudspeaker or microphone. This fiber acoustic transducer demonstrates interesting properties including generating directional sound as a loudspeaker and locating sound source as a microphone. Besides, the good flexibility allows it to be woven into textiles for various significant applications such as emergency rescue activities. This work represents a new direction in the

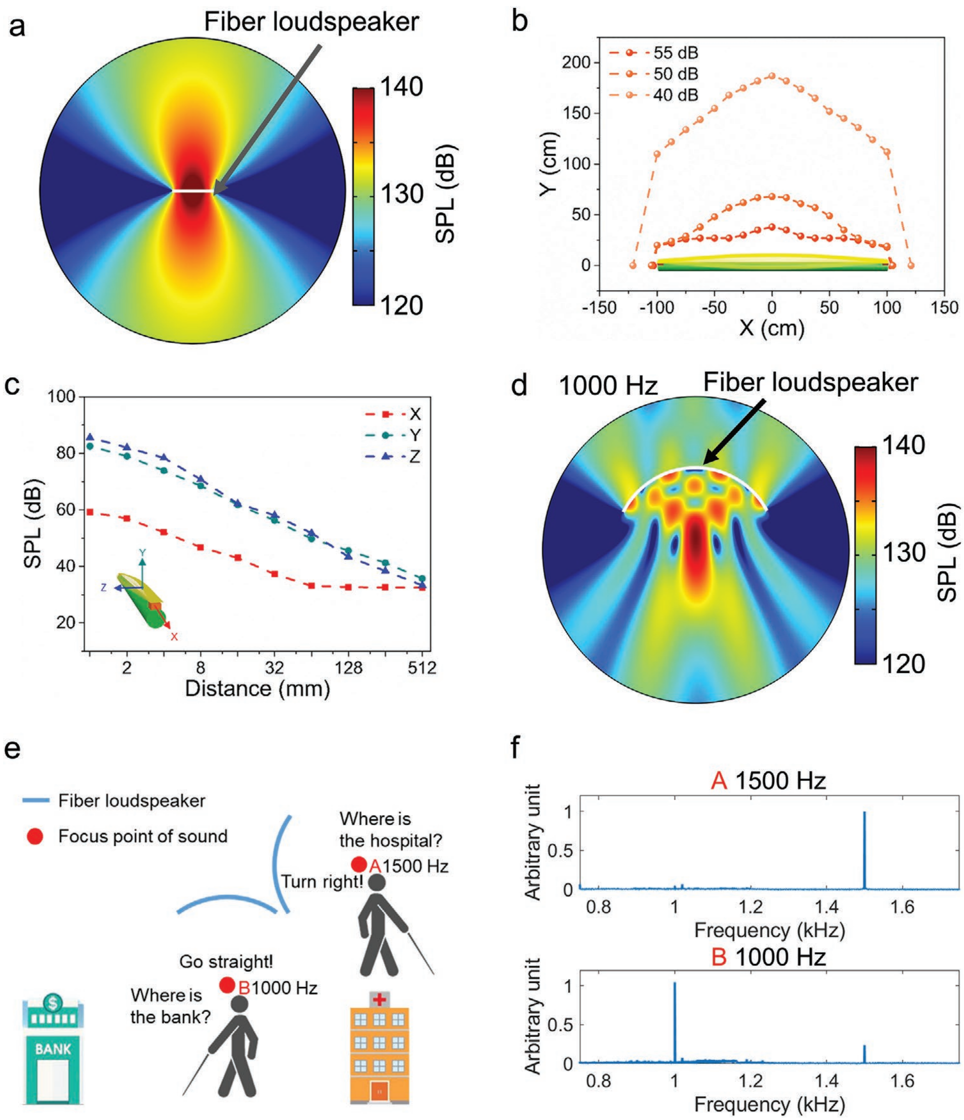

Figure 3. Performance and application of the fiber acoustic transducer as a loudspeaker based on its directional sound. a,b) Finite element analysis and experimental results of the SPL distribution around a straight fiber loudspeaker with a length of 20 cm, respectively. c) Experimental results of SPL anisotropy of fiber loudspeaker in axial direction and radical directions. d) Finite element analysis of the SPL distribution around a fiber loudspeaker that was bent into a circular arc configuration at 1000 Hz. e) Application scenarios of two fiber loudspeakers guiding two blind people at Spot A and Spot B respectively at the same time via directional sound. f) Experimental results of the frequency spectrum at Spot A and Spot B.

development of next-generation acoustic transducers as a necessary constructing unit of future smart textiles.

4. Experimental Section

Fabrication of Fiber Acoustic Transducer: NdFeB magnet fiber with a thickness of 1 mm was obtained from Earth-Panda (Suzhou). Aluminum foil with a thickness of 10 µm was obtained from Yong Wang (Shanghai) and further cut into fibers with a width of 1 mm. Aluminum foil fiber was attached on the pole of the NdFeB magnet fiber by acrylic adhesives with an interval of 25 mm. The fiber acoustic transducer could be continuously produced by a home-made machine assembled from LEGO NXT that was controlled by a software of NXT 2.1 Programming.

Measurement of Acoustic Performance of Fiber Loudspeaker: SPL was measured by a microphone (Umik-1, miniDSP) connected to a laptop with REW (Room EQ Wizard) software. The alternating voltage generated in the headphone jack of a laptop (HASEE G9-CU7PK) was amplified by a power amplifier (FeelTech FPA101A) and then reached the electrodes of the fiber loudspeaker to generate sound. Measurements were performed in a semianechoic room with 18 dB background noise. The microphone was placed 1 cm away from the fiber loudspeaker during SPL measurements. The detection of the vibration was carried out by a Free-space Single-point Laser Doppler Vibrometer (HoloBright FNV-R1D-VD1). The time-frequency analysis was carried out by the MATLAB software after recording the sound signals generated by a fiber loudspeaker. The temperature was traced by an infrared thermal imager (Optris PI) combined with an analysis software (Optris PIX Connect). In the directional sound demonstration (Figure 3e,f), two fiber loudspeakers were placed in a shape of semicircle with a radius of 640 mm. They produced notify sounds with different frequencies of 1000 and 1500 Hz, respectively. The sounds were then collected at the centers of semicircles (Spots A and B).

Measurement of Acoustic Performance of Fiber Microphone: The sound was generated by the loudspeaker of a laptop (HASEE G9-CU7PK). The fiber microphone was connected to the microphone jack of the laptop

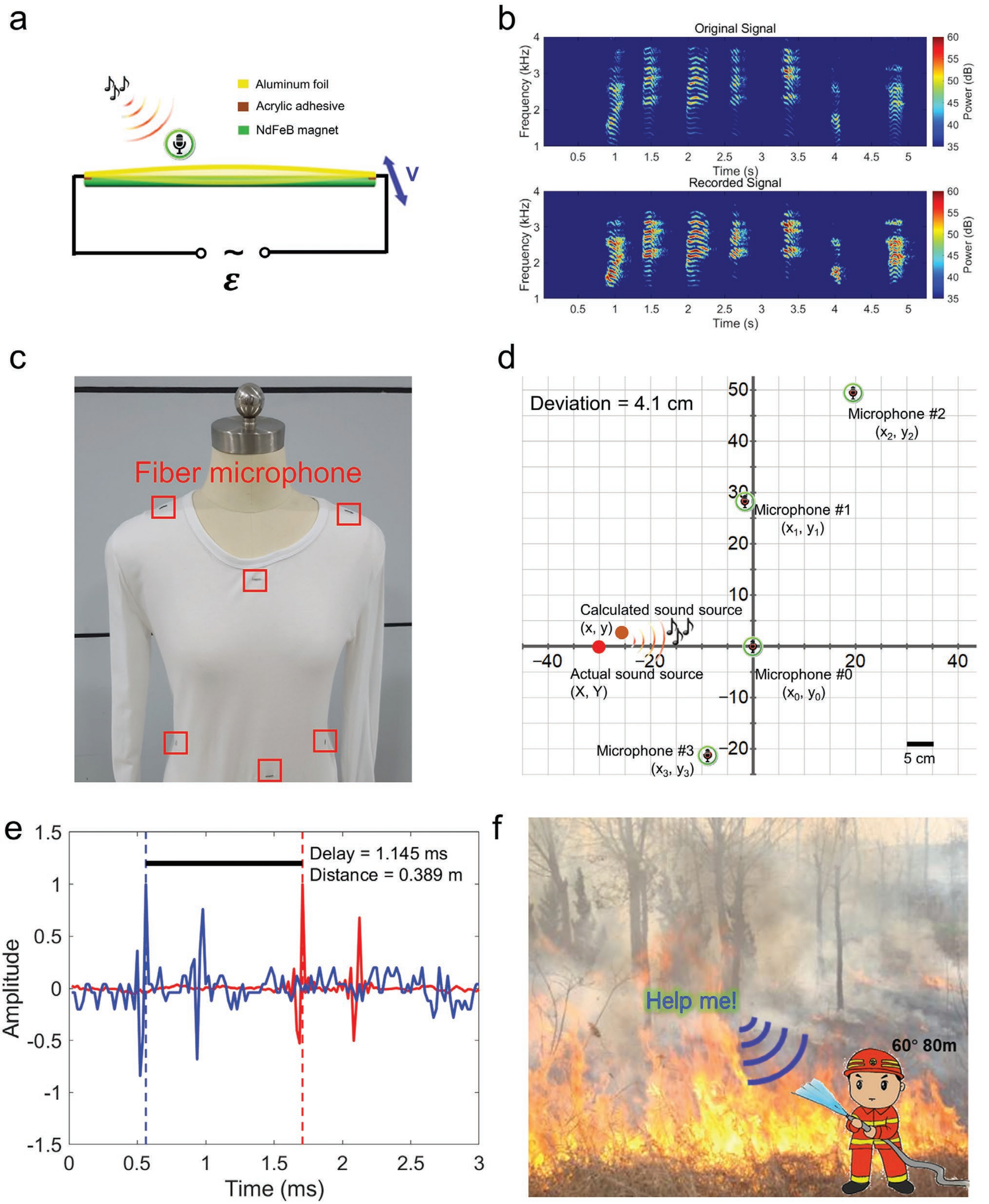

Figure 4. Acoustic performance and application of the fiber acoustic transducer functioning as a fiber microphone. a) Schematic illustration of the working mechanism. b) Time-frequency analysis of original and recorded sound waves by the fiber microphone. c) A sound source location cloth woven with fiber microphones at different positions. d) The coordinates of actual sound source, calculated sound source and four fiber microphones. The origin of the coordinates is located at the position of Microphone #0. e) Time delay caused by the distance difference from sound source to Microphone #2 and #0. f) Conceptual application scenario of the sound source location cloth.

(HASEE G9-CU7PK). The audio was recorded and processed by an Au software (Adobe Audition CC 2018). In the sound source localization experiment, the sound signal collected by the fiber microphones woven in the cloth was processed using MATLAB R2020a.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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