Single fiber enables acoustic fabrics via nanometer scale vibrations

Wei Yan[1,2], Grace Noel[3], Gabriel Loke[1,2,13], Elizabeth Meiklejohn[4,13], Tural Khudiyev[1,13], Juliette Marion[2,13], Guanchun Rui[5], Jinuan Lin[6], Juliana Cherston[7], Atharva Sahasrabudhe[1,8], Joao Wilbert[7], Irmandy Wicaksono[7], Reed W. Hoyt[9], Anais Missakian[4], Lei Zhu[5], Chu Ma[6] John Joannopoulos[10,11], Yoel Fink[1,2,12*]

[1] Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[2] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[3] Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[4] Textile Department, Rhode Island School of Design, Providence, RI 02903, USA

[5]Department of Macromolecular Science and Engineering, Case Western Reserve University, Cleveland, OH, 44106-7202, USA

[6] Department of Electrical and Computer Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, Madison, Wisconsin 53706, USA

[7] Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[8] Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[9] U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760, USA

[10] Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[11] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[12] Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[13] These authors contributed equally.

*E-mail: yoel@mit.edu

Fabrics, by virtue of their composition and structure, have traditionally been utilized as acoustic absorbers[1,2]. Here inspired by the auditory system[3], we introduce a fabric that operates as a sensitive audible microphone while retaining the traditional qualities of fabrics, like machine washability and draping. The fabric medium is composed of high modulus textile yarns in the weft of a cotton warp, converting tenuous 10^{-7} atm pressure waves at audible frequencies into lower order mechanical vibration modes. Woven into the fabric is a thermally-drawn composite piezoelectric fiber which conforms to the fabric and converts the mechanical vibrations into electrical signals. Key to the fiber sensitivity is an elastomeric cladding which concentrates the mechanical stress in a piezocomposite with a high d_{31} ~46 pC/N, a result of the thermal drawing process. Concurrent measurements of electric output and spatial vibration patterns in response to audible acoustic excitation reveal that fabric vibrational modes with nanometer amplitude displacement are the source of the fiber's electrical output. With the fiber subsuming less than 0.1 vol.% of the fabric, a single fiber draw enables tens of square meters of fabric microphone. Three different applications exemplify the usefulness of this study: a woven shirt with dual acoustic fibers measures the precise direction of an acoustic impulse, bi-directional communications are established between two fabrics working as sound emitters and receivers, and a worn shirt auscultates cardiac sound signals.

Main

The ubiquity of fabrics, together with recent breakthroughs in fiber technology, allow us to challenge traditional uses of fabrics to encompass new and potentially useful roles[4,5,6,7,8]. Fabrics have recently been shown to store energy[9], communicate[10], heat[11], cool[12,13], display[14], and even store and process digital information[15]. Motivated by the extent of fabric usage, its unparalleled proximity to the human body, and the significance of acoustic signals, we set out to investigate whether fabrics could serve as efficient sound collectors to detect and process even faint audible signals. The consequences of such a transformation in fabric use would be far-reaching—enabling fabrics to mediate acoustic communications, pick up acoustic health indicators from the body, and increase situational acoustic awareness.

Achieving sensitive acoustic fabrics faces two major obstacles. First, traditional fabrics are notorious for damping sound, and second, previously reported fibers capable of converting mechanical vibrations into electrical signals suffer from low sensitivity in air[16,17]. Fabrics are hierarchical constructs made of staple or filament fibers that are twisted into yarns and then assembled into fabrics. This hierarchy inherently establishes multiple interfaces, which scatter and dissipate propagating phonons, giving fabrics dissipative acoustic characteristics. In nature, however, fibers often serve the purpose of transmitting sounds rather than damping them. For example, in the human auditory system (**Fig. 1**), the tympanic membrane is responsible for resolving the acoustic impedance mismatch between the air of the ear canal and the fluid of the inner ear and happens to be a construct of high modulus fibers oriented circumferentially and radially[18]. This membrane transduces sound pressure to mechanical vibrations of the middle ear bones. Such vibrations are then transmitted to the cochlea of the inner ear. In the cochlea, hair bundles are deflected to ultimately convert pressure waves into electrical signals (ionic) that are picked up by the nervous system[3]. Drawing inspiration from the auditory transduction sequence involving conversion of pressure to mechanical to electrical excitations and the importance of fibers in the auditory system, we introduce an approach with a similar transduction path that harnesses fibers to enable a minimally perturbed fabric to efficiently convert pressure waves to electrical output (**Fig. 1**).

Unlike the complex 3D auditory system, we seek to achieve this conversion in a planar fabric. The fabric medium will play the role of the tympanic membrane to convert pressure waves into mechanical vibrations of a membrane. Woven into the fabric, the fiber transducer will play a similar role to the cochlea in providing electrical output. Given the conformal nature of the fiber, effective coupling, which is necessary for efficient conversion, occurs between the fabric and the fiber to form an acoustic fabric. Using a uniform membrane as a model for the eventual fabric medium, we begin with constructing a piezoelectric fiber that efficiently converts the membrane's vibrations into electrical output. We then employ laser vibrometry with concurrent electrical measurements to study the displacement modes of the membrane and fiber and elucidate the conversion mechanism. This guides the design of the woven acoustic fabrics, which detect nanometer displacement generated by audible acoustic waves, producing coherent electrical signals.

Fiber design and fabrication

Figure 2a outlines the piezoelectric fiber design and fabrication. The process begins with the construction of a macroscopic preform. The active layer is a composite consisting of the piezoelectric poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) loaded with piezoelectric barium titanate ($BaTiO_3$) ceramic particles (**Extended Data Fig. 1**). P(VDF-TrFE) has a melting point of 150 °C (**Extended Data Fig. 2**), making it suitable for co-drawing with the other fiber materials. CPE's high viscosity at the draw temperature delays the onset of capillary instability of the low viscosity crystalline piezoelectric domain. During the draw, four copper wires are fed into the empty channels of the CPE, which in concert deliver excellent conductivity across two length scales—the microscale cross section and the meter-scale fiber length. The innermost layers are asymmetrically encapsulated within an elastic poly(styrene-b-(ethylene-co-butylene)-b-styrene) (SEBS) cladding[19] (**Fig. 2a**) (See Methods).

The preform is then thermally drawn into tens of meters of a fiber with sub-millimeter features. At the high voltages required by the poling step, small deviations in the thickness of the piezoelectric layer can lead to breakdown of the composite[20]. The required level of precise dimensional control is demonstrated by the production of a highly uniform 40-meter-long fiber (**Fig. 2b**). The stable flow of all the materials preserves the cross-section geometry from the preform to the fiber. The interfaces between the P(VDF-TrFE)/$BaTiO_3$ and the CPE electrodes formed during the draw exhibit good adhesion **(Fig. 2e)**. The nanoparticles maintain their homogenous distribution during the viscous flow (**Fig. 2e**). The thermal drawing process aligns the polymer chains along the draw direction (**Extended Data Fig. 1c**). The $BaTiO_3$ nanoparticles maintain their monocrystalline tetragonal phase (**Extended Data Fig. 1d**), and the introduction of nanoparticles into the P(VDF-TrFE) does not deteriorate its flexibility (**Supplementary Fig. 5**)

The fiber loaded with 20 wt% $BaTiO_3$ nanoparticles exhibits significantly improved ferroelectric properties with a remanent polarization as high as 10 $\mu C/cm^2$ (**Extended Data Fig. 2a**). To achieve a highly sensitive sound transducer, we develop a step-wise poling method to align the dipoles in the piezocomposite (**Extended Data Fig. 2b**). Alternating the increasing applied voltage with 0 V relaxation periods not only mitigates the risk of dielectric breakdown during the poling process but also endows the composite with excellent piezoelectric properties[21]. We measured the piezoelectric charge coefficient d_{31} to be as high as ~46 pC/N, significantly higher than that of the drawn P(VDF-TrFE) fiber (~20 pC/N) of and hot-pressed P(VDF-TrFE)/$BaTiO_3$ composite (~10 pC/N) (**Fig. 2f**) as well as superior to existing PVDF-based piezoelectric materials (**Extended Data Table 1**). Microscopic analysis identifies voids around the $BaTiO_3$ particles observed only in the drawn fiber, suggesting the existence of a porous ferroelectret structure due to cavitation[22] between the $BaTiO_3$ particles and the P(VDF-TrFE) matrix. This structure can provide one explanation for the comparatively high d_{31} observed only in the drawn fiber (**Supplementary Note 2**).

The use of the elastomeric thermoplastic as the fiber cladding is motivated by many considerations. First, the combination of this elastomeric cladding with the stiffer piezoelectric composite results in stress concentration in the active piezoelectric domain (**Fig. 2g** and **Supplementary Fig. 12**). Second, the SEBS cladding's low modulus contributes to the fiber bending compliance, an important aspect when designing a fiber that needs to conformally match to membrane vibration modes. The flexibility is also key to machine weaving into fabrics. Lastly, SEBS possesses excellent rheological properties (**Extended Data Fig. 3**), enabling preservation of the cross-sectional geometry of the resulting fiber. Owing to the low Young's modulus (3.79 MPa, **Supplementary Fig. 13**), the fiber tolerates some sophisticated deformations such as bending and twisting (**Fig. 2c and d**). Its capacitance remains stable over 3000 cycles of bending or twisting (**Extended Data Fig. 4**). The 10 machine-washing tests further demonstrate its high reliability and mechanical compliance. (**Supplementary Fig. 14**).

Fiber-on-membrane model

Once drawn and poled, the standalone piezoelectric fiber responds to acoustic waves in the audible range (**Fig. 3a**). When the fiber is mounted on a Mylar membrane the electrical output is significantly larger. The boundary condition of the membrane should be well controlled via clamping and tensioning to achieve reproducible, reliable results (**Supplementary Note 5**). The output voltage of the fiber-on-membrane is measured in response to continuous waves generated by a speaker in the audible range under the sound pressure level (SPL) of 60 dB ($\sim 10^{-7}$ atm) or at a fixed frequency under different SPLs. The strong coupling between the fiber and the membrane mechanical vibration modes produces an electrical output that is two orders of magnitude higher than that of the standalone fiber (**Fig. 3a**). The output voltage (several orders of magnitude higher than the noise level) increases linearly with increasing SPL, consistent with the typical acoustic response of linear materials[23]. The minimum sound-detection capability is 0.002 Pa (40 dB, SPL in a quiet library), outperforming many other thin-film-based acoustic sensors[24,25,26]. The high Young's modulus membrane experiences minimal losses, allowing the system to efficiently record a short impulse with high fidelity (**Fig. 3b**), as elaborated on in the next section.

A sensitivity of 19.6 mV (at 94 dB and 1 kHz, following standards in the field) of the fiber-on-membrane is measured, which is comparable to off-the-shelf condenser and dynamic microphones (**Supplementary Table 3**). The high sensitivity allows it to efficiently detect audible sounds, as demonstrated by the high signal-to-noise ratio of the measured voltage output when the system is subject to a wide range of sound sources, such as human speech, air blowing, leaves rustling, and birds chirping (**Supplementary Video 1** and **Extended Data Fig. 5**).

Transduction mechanism

To reveal the transduction mechanism of the fiber woven into a fabric, we begin by examining the simpler model of fiber-on-membrane described above. A speaker illuminates the fiber-on-membrane with audible acoustic waves (**Fig. 3)**. A scanning laser vibrometer measures the vibration of the membrane as a displacement map at various frequencies. Meanwhile, we measure the output voltage from the fiber. These simultaneous measurements allow us to correlate the electrical output from the fiber with the mechanical vibration modes of the membrane. The output voltage vs. frequency in **Fig. 3c** shows a large peak of 8 millivolts at 300 Hz, followed by peaks of decreasing amplitude as the frequency increases. At 550Hz, for example, the electrical output is 0.5 millivolts. Displacement maps reveal that at 300Hz the membrane displays a low order symmetric resonant vibration mode with large amplitude of ~950 nm, while at 550 Hz, the mode is antisymmetric and has a much smaller amplitude of ~110 nm.

A 3D acoustical-mechano-electro model (COMSOL Multiphysics) is developed to gain insights into the fiber-on-membrane using sinusoidal plane acoustic waves as the input and the electrical signal from the fiber as the output. The simulation results reveal that the dominant factor determining the fiber electrical output is its axial bending (**Extended Data Fig. 6**) which occurs when the fiber is conformally displaced by the membrane vibration modes.

Our measurements and simulations (and the Euler-Bernoulli beam theory see **Supplementary Note 7**) reveal two main factors influencing the magnitude of the system's electrical output. First, larger membrane displacement amplitudes associated with lower order resonances result in a larger curvature of the fiber and thus more strain in the piezocomposite. Second, the curvature integral along the fiber length is correlated to the fiber's electrical output. When the fiber curvature has the same sign along its length, the piezoelectric layer is subject to similar stress conditions (either tensile or compressive) and charges of the same type (either positive or negative) build up additively on the electrodes, leading to a high output voltage. When the curvature changes sign along the fiber length, the piezoelectric layer undergoes tensile and compressive stress at different locations, resulting in charge cancellation that reduces the output voltage (**Fig. 3c**). The curvature changes signs more rapidly along the fiber in higher order modes, resulting in lower output voltage.

The simulations do not account for damping or modulus dispersion. It is reasonable, however, to expect that the overall decrease in performance with frequency is due to the higher damping of the mechanical vibrations of the membrane at higher frequencies[27] and the stiffening of the SEBS at higher frequencies leading to larger resistance to deformation.

The fiber displacement and its curvature are influenced by the geometrical (shape, size, thickness, boundary conditions, etc.) and mechanical properties (density, Young's modulus, Poisson's ratio, etc.) of the membrane. One can however heuristically conclude that when the vibration half wavelength of the fiber matches the size of the membrane the signal is maximal. This is achieved by selecting a membrane that has a high modulus resulting in fewer oscillations per unit membrane length, lower order resonances[27], and thus large electrical output.

Woven acoustic fabric fabrication and characterization

Armed with these insights into the mechanism of transduction, we proceed to explore fabric designs optimized for acoustic collection and conversion. We construct two plain weave fabrics with different Young's moduli using a conventional weaving loom (**Fig. 4a**). The first fabric consists of cotton yarns in both the warp and the weft directions (**Fig. 4c**). This fabric has a lower modulus and is constructed of staple yarns. The second fabric has the same cotton warp but high modulus Twaron filament yarns in the weft direction (**Fig. 4b and c**). The two fabrics have the same thickness, weight, and dimensions but differ in their moduli and the use of filament vs. staple. The fiber transducer is woven into the fabrics. The tension of the warp cotton yarns that cross over the acoustic fiber is well controlled so that the fiber is not severely compressed. The fabric samples are then mounted on a frame with well-controlled boundary conditions (**Supplementary Fig. 18**). The frequency response characterization reveals that the Twaron-weft fabric outperforms the cotton fabric (**Fig. 4c**). Note that the fabrics show excellent electrical signals at audible frequencies regardless of the specifics of tension or boundary conditions (**Extended Data Fig. 7** and **Supplementary Video 2**).

The vibrational behavior of the two fabrics at some representative frequencies is summarized in **Fig. 4d**, which reveals that nanometer displacement generated by audible acoustic waves can be efficiently detected and amplified in fabrics forming coherent electrical detection of sound. The anisotropic vibrational wavelength (longer wavelength on the weft and shorter wavelength on the warp) of the Twaron/cotton fabric and the isotropic vibrational wavelength (identical wavelength on both the weft and the warp) of the cotton fabric are notably revealed. At 230 Hz, a resonance frequency of the Twaron/cotton fabric, the modes of the fabric are of lower order and longer wavelength compared to those of the pure cotton fabric at 240 Hz. Shown also is the fiber displacement for these two fabrics with the curvature all having the same sign for the Twaron/cotton case while changing sign for the cotton. Similarly, owing to the lower order modes of the Twaron/cotton fabric at the anti-resonance frequency of 320 Hz compared to those of the cotton fabric at 460Hz, the bending wavelength of the fiber in the Twaron/cotton is much longer than that in the cotton. The electrical output for bending modes involves integration over the curvature function which, when changing signs, leads to a cancellation effect and a diminishing output.

The magnitude of the fiber output depends on the order of the mode, its wavelength, and the fabric dimensions, which together yield different curvature integrals and electrical outputs. The sensitivity of the two-dimensional fabric microphone reaches 8 mV, attributed both to the high modulus and also to the lower losses associated with continuous filament, which compares well with many commercialized condenser and dynamic point microphones (**Supplementary Table 3**), demonstrating that indeed, fabrics can function as efficient sound collectors and transducers in the audible frequency range.

The scalability of the thermal drawing approach is well matched with the scale of industrial weaving processes (**Fig. 4a**). A typical acoustic fabric (36 cm ×23 cm) shown in **Supplementary Video 2** only contains ~6.7 cm of fiber that occupies ~0.1% of the volume of the fabric (Methods). In our study, 40 meters of fiber are drawn from a preform in a single draw. This length can produce nearly 50 square meters of acoustic fabric. The fabric maintains its electrical properties and acoustic sensitivity after ten machine-wash cycles (**Extended Data Fig. 8**).

Exemplary applications

The performance and form-factor of the acoustic fibers enable a wide range of applications (**Fig. 5)**. Here, the woven Twaron/cotton fabric is integrated into shirts. All the shirts are in a flexurally slack, draped condition (**Supplementary Video 2**). In **Fig. 5a**, the direction of an impulse is discerned by a shirt containing two fibers. A hand clap is initiated at various angles and the output from each fiber is recorded. The time delay between the peaks corresponds to a difference in the path length to the individual fibers, allowing for precise derivation of the direction of the clap. Directional detection could be useful for individuals with hearing aids to listen in specific directions while removing background noise, and for law enforcement seeking to detect a source of a gunshot. In addition to sensing sound, the fabric can also broadcast audible sounds when a modulated AC voltage is provided (**Supplementary Video 3 showing a fiber playing music**). As illustrated in **Fig. 5b, Extended Data Fig. 9 and Supplementary Video 4**, two shirts enable bi-directional acoustic communication with matched time-domain waveforms and frequency-domain spectrograms between the emitted speech and the received speech, facilitating acoustic communication between individuals, which may be useful for the hearing impaired, covert communications, or even underwater communications. With their high sensitivity to vibrations and matched impedance with the skin, the fabrics are particularly suited for physiological sensing. Heart auscultation is a fundamental tool in the diagnosis of cardiovascular diseases and abnormalities. **Fig. 5c** shows that an acoustic shirt contacting to the chest of a person efficiently captures cardiac signals, acting as a skin-interfaced stethoscope. The signal, with a signal-to-noise ratio as high as 30 dB, surpasses recent thin-film acoustic devices[28,29] and conveys useful information about the wearer’s cardiovascular system. The resting heart rate is measured to be 70 beats per minute. The shirt also clearly detects the louder S1 sound and the weaker S2 sound. Most strikingly, the fiber itself captures the splitting of S1 as well as the splitting of S2 (**Supplementary Fig. 30**), previously unachievable with thin-film devices[28,29]. **Supplementary Audio 1** presents high-quality heart sounds recorded using the acoustic shirt. The ability to detect the mechanical action of the heart using the fabric may enable wearers to monitor their heart and respiratory condition in a comfortable, continuous, real-time, and long-term manner.

In summary, the principles, materials, and mechanisms leading to the realization of the first acoustic fabric are revealed. The resulting fabrics are capable of efficiently detecting audible sounds with performance on par with commercial microphones. Applications in sound direction detection, acoustic communications, and heart sound auscultation illustrate the wide-ranging applicability of this technology to enable advances in computing fabrics[30], security[31], aerospace engineering[32], communications[33], biomedicine[34] and robotics[35].

References:

1. Delany, M. E. & Bazley, E. N. Acoustical properties of fibrous absorbent materials. *Appl. Acoust.* **3**, 105–116 (1970).
2. Tang, X. & Yan, X. Acoustic energy absorption properties of fibrous materials: A review. *Compos. Part A Appl. Sci. Manuf.* **101**, 360–380 (2017).
3. Kozlov, A. S., Baumgart, J., Risler, T., Versteegh, C. P. C. & Hudspeth, A. J. Forces between clustered stereocilia minimize friction in the ear on a subnanometre scale. *Nature* **474**, 376–379 (2011).
4. Shi, J. et al. Smart Textile-Integrated Microelectronic Systems for Wearable Applications. *Adv. Mater.* **32**, 1901958 (2019).
5. Abouraddy, A. F. *et al.* Towards multimaterial multifunctional fibres that see, hear, sense and communicate. *Nat. Mater.* **6,** 336–347(2007).
6. Yan, W. *et al.* Thermally drawn advanced functional fibers: New frontier of flexible electronics. *Mater. Today* **35**, 168–194 (2020).
7. Weng, W. et al. A Route Toward Smart System Integration: From Fiber Design to Device Construction. *Adv. Mater.* **32**, 1902301 (2020).
8. Chen, G., Li, Y., Bick, M. & Chen, J. Smart Textiles for Electricity Generation. *Chem. Rev.* **120**, 3668–3720 (2020).
9. Khudiyev, T. et al. 100 m Long Thermally Drawn Supercapacitor Fibers with Applications to 3D Printing and Textiles. *Adv. Mater.* **32**, 2004971 (2020).
10. Rein, M. et al. Diode fibres for fabric-based optical communications. *Nature* **560**, 214–218 (2018).
11. Zhang, X. A. et al. Dynamic gating of infrared radiation in a textile. *Science* **363**, 619–623 (2019).
12. Hsu, P. C. et al. Radiative human body cooling by nanoporous polyethylene textile. *Science* **353**, 1019–1023 (2016).
13. Zhu, B. et al. Subambient daytime radiative cooling textile based on nanoprocessed silk. *Nat. Nanotechnol.* **16**, 1342–1348 (2021).

14. Shi, X. et al. Large-area display textiles integrated with functional systems. *Nature* **591**, 240–245 (2021).

15. Loke, G. *et al.* Digital electronics in fibres enable fabric-based machine-learning inference. *Nat. Commun.* **12,** 3317 (2021).

16. Egusa, S. et al. Multimaterial piezoelectric fibres. *Nat. Mater.* **9**, 643–648 (2010).

17. Chocat, N. et al. Piezoelectric fibers for conformal acoustics. *Adv. Mater.* **24**, 5327–5332 (2012).

18. Fay, J. P., Puria, S. & Steele, C. R. The discordant eardrum. *Proc. Natl. Acad. Sci. USA* **103**, 19743–19748 (2006).

19. Qu, Y. *et al.* Superelastic Multimaterial Electronic and Photonic Fibers and Devices via Thermal Drawing. *Adv. Mater.* **30**, 1707251 (2018).

20. Acosta, M. et al. BaTiO3-based piezoelectrics: Fundamentals, current status, and perspectives. *Appl. Phys. Rev.* **4**, 041305 (2017).

21. Setiadi, D., Binnie, T. D., Regtien, P. & Wubbenhorst, M. Poling of VDF/TrFE copolymers using a step-wise method. *9th Int. Symp. Electrets (ISE)* 831-835 (1996).

22. Zhang, Y., Bowen, C. R. & Deville, S. Ice-templated poly(vinylidene fluoride) ferroelectrets. *Soft Matter* **15**, 825–832 (2019).

23. Safari, A. & Akdogan, E. K. Piezoelectric and acoustic materials for transducer applications. Springer (2008).

24. Lang, C., Fang, J., Shao, H., Ding, X. & Lin, T. High-sensitivity acoustic sensors from nanofibre webs. *Nat. Commun.* **7**, 11108 (2016).

25. Kang, S. et al. Transparent and conductive nanomembranes with orthogonal silver nanowire arrays for skin-attachable loudspeakers and microphones. *Sci. Adv.* **4**, eaas8772 (2018).

26. Khan, A., Abas, Z., Soo Kim, H. & Oh, I. K. Piezoelectric thin films: An integrated review of transducers and energy harvesting. *Smart Mater. Struct.* **25**, 053002 (2016).

27. Kinsler, L., Frey, A., Coppens, A. & Sanders, J. Fundamentals of Acoustics. John Wiley & Sons, Inc., (2000).

28. Yang, Y. & Gao, W. Wearable and flexible electronics for continuous molecular monitoring. *Chem. Soc. Rev.* **48**, 1465–1491 (2019).

29. Xiong, J., Chen, J. & Lee, P. S. Functional Fibers and Fabrics for Soft Robotics, Wearables, and Human–Robot Interface. *Adv. Mater.* **33**, 2002640(2021).

30. Loke, G. et al. Computing Fabrics. *Matter* **2,** 786–788 (2020).

31. Clavel, C. & Ehrette, T. Fear-type emotion recognition and abnormal events detection for an audio-based surveillance system. *WIT Trans. Inf. Commun. Technol.* **39**, 471–479 (2008).

32. Ahmed, A., Hossain, M. M., Adak, B. & Mukhopadhyay, S. Recent Advances in 2D MXene Integrated Smart-Textile Interfaces for Multifunctional Applications. *Chem. Mater.* **32**, 10296–10320 (2020).

33. Cummer, S. A., Christensen, J. & Alù, A. Controlling sound with acoustic metamaterials. *Nat. Rev. Mater.* **1**, 16001 (2016).

34. Han, M. et al. Three-dimensional piezoelectric polymer microsystems for vibrational energy harvesting, robotic interfaces and biomedical implants. *Nat. Electron.* **2**, 26–35 (2019).

35. Yang, G.-Z. et al. The grand challenges of Science Robotics. *Sci. Rob.* **3**, eaar7650 (2018).

Figure Legends

Fig. 1 | Design and principles of fabric microphones. Top, The tympanic membrane is a four-layer construct composed of circumferential- and radial-oriented high modulus collagen fibers, which are key for sound conduction. The tympanic membrane motion is ultimately transmitted to the cochlea through the basilar membrane, wherein short cilia fibers convert pressure waves into electrical signals (ionic) which are picked up by the nervous system. **Bottom,** In the acoustic fabric, high modulus Twaron yarns and cotton yarns are oriented at right angles, mimicking the construction of the tympanic membrane. This construction converts faint audible frequency sound pressure waves into low order mechanical vibration modes. Within that same medium, a single strand of piezoelectric elastomeric fiber transducer is woven, leading to a synergistically coupled fabric, where sound transduction is in fact a collective effect. This results in a fabric capable of operating as a sensitive microphone that detects weak sound signals (e.g., human speech) as low as 10^{-7} atm.

Fig. 2 | Acoustic fiber fabrication and characterization. a, Schematic of preform-to-fiber thermal drawing and fiber poling. **b,** Photograph of some portions of the 40-meter-long fiber wrapped on a spool. **c,** Photograph of a piece of fiber wrapped on a finger, showing its high flexibility. **d,** Photograph of a piece of fiber that is twisted with an angle of 180°. **e,** (**e-1**) Scanning Electron Microscopy (SEM) micrograph of the fiber cross-section showing the fiber geometry is preserved after thermal drawing of the macroscopic preform. The gaps between the Cu wires and the surrounding CPE electrodes were created during the cleaving process. (**e-2**) High-resolution

SEM micrograph showing the intimate interface between the CPE electrodes and the piezocomposite; (**e-3**) High-resolution SEM micrograph showing the homogenous distribution of $BaTiO_3$ nanoparticles in the P(VDF-TrFE) matrix. **f,** Measured d_{31} piezoelectric coefficients of the hot-pressed composite, drawn P(VDF-TrFE) fiber, and drawn P(VDF-TrFE)/BTO fiber. **g,** Simulated von Mises stress distribution in the cross-section of the fiber cladded by the SEBS cladding at 290 Hz. Higher stress leads to higher output voltage for the piezocomposite. More details about simulation are shown in Methods and Supplementary Note 8.

Fig. 3 | Acoustic fiber on membrane characterization. The schematic shows the concurrent measurement. The continuous sound waves are generated from a speaker while the impulse is generated from a clap. The vibration modes of the membrane under the impact of the continuous sound waves generated from the speaker are measured. **a,** The output voltage versus sound pressure of the fiber-on-Mylar system at 1000 Hz. The performance of the standalone fiber is presented for a comparison. The noise level is also shown. **b,** The output voltage of the fiber-on-Mylar system in response to a clap. (Note that the this is the voltage after it has been amplified 68x.) **c,** left: Measured vibrational (1, 1) modes together with *z* displacement (perpendicular to membrane surface) of the membrane and fiber at a resonance frequency of 300 Hz. middle: Measured frequency response of the sample from 80 to 1000 Hz. right: Measured vibrational (1, 2) modes together with z displacement (perpendicular to membrane surface) of the membrane and fiber at an anti-resonance frequency of 550 Hz. Since the laser vibrometer is reading the back side of the membrane we infer the fiber displacement by measuring the membrane displacement behind it. The positive and negative signs on the displacement curves represent generated charges. Locations with higher curvatures have higher charge densities. The fiber is located vertically in the center of the membrane (8 cm by 8 cm). The voltage measurements were repeated three times. After the first measurement, the fiber was removed from the sample and re-attached for the next measurement. The error is the standard deviation of the three measurements.

Fig. 4 | Fabrication and characterization of woven acoustic fabrics. **a,** The fiber with a length of ~70 m is incorporated into the fabric during the weaving process. Note that the photograph of the fiber-on-spool on the left is magnified with respect to the fabric to better exhibit the fiber. **b,** The photograph of the Twaron-weft acoustic fiber containing one fiber transducer (6.7 cm in length) woven in the weft. **c,** The fabric was fixed in a frame (8 cm by 8 cm) with well-controlled boundary conditions (**Supplementary Note 5**) for acoustic characterization. Measured frequency response of the fabric sample (8 cm by 8 cm). The schematics of the Twaron/cotton fabric and the cotton fabric are also shown. Note that warp yarns are shown horizontally and weft yarns are shown vertically. **d,** Measured vibrational modes together with *z* displacement (perpendicular to membrane surface) of the two fabrics and fibers at their resonance and anti-resonance frequencies using the laser vibrometer.

Figure 5: Examples of applications of the woven acoustic fabric integrated into shirts. a, Sound direction detection: **a-1,** A shirt containing two fibers separated by some distance is used to detect the direction of the sound source. **a-2,** The fabric is modified by removing a section of the weft yarns to acoustically insulate the two fibers. **a-3,** The time difference between the peaks of the signal curve results in an estimated angle of 19.7°, which is 0.3° from the measured angle of 20°. **a-4 and 5,** Angles from -60° to 60° were tested with a clap at a distance of 3 m, and the overall average error was 1.73°. At an angle greater than 60 degrees, the impact of the sound waves on the fabric is reduced, making the peak detection difficult if the distance of the clap remains at 3 m. **b,** Acoustic communication application: **b-1,** Acoustic fabrics could enable communications between individuals suffering from speech or hearing impairments. **b-2,** Demonstration of acoustic communication using two shirts: one serves as a microphone and the other works as a speaker. The speech of "The acoustic fabric records audible sound" emitted by one shirt is recorded by the other shirt (**Supplementary Video 4**). **c,** Fabric stethoscope application: **c-1,** Photograph of the experimental scenario. **c-2,** The shirt interfacing the chest can detect heart sound with the information of the heart rate, both the S1 and S2 components of the heart sound, as well as the split of S1 and S2. For all the measurements, the participant gave informed consent.

Methods

Preparation of Nanostructured Piezoelectric Composites

Poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFe, Piezotech FC 30) with 30 mol% TrFe was dissolved in dimethylformamide (1:10, w:w) by continuous stirring for 5 h. Barium titanate particles (spherical, 99.9%, 200 nm, Tetragonal phase, US Research Nanomaterials, Inc) (average diameter of 260 nm is shown in Supplementary Fig. 32) were added and stirred for 12 h to form a suspension. The ratio of $BaTiO_3$ to PVDF-TrFE is 1:5 by weight. The suspension was sonicated for 2 h, changing the water every 15 min to prevent it from warming up. The suspension was stirred again for 20 h, and then sonicated for 3 h, changing the water every 15 min. It was then mixed in a centrifugal mixer at 3500 rpm for 10 minutes. The mixture was poured onto a glass substrate to form a film as the DMF evaporates. After drying at room temperature for one day, the composite separates from the solvent and forms a film at the bottom of the dish with the DMF solvent on top. The film is removed from the DMF and dried in a 60°C oven for five days before use.

Preform Fabrication and Thermal Drawing

The acoustic fiber was drawn from a macroscopic rectangular preform with dimensions of 2.5 x 1.38 x 18 cm. A hot press was used to press the piezocomposite, CPE (ET331080, Goodfellow, UK), and SEBS (grade G1657 from Kraton Performance Polymers Inc) layers into sheets of the appropriate thickness. All the materials were then cut and assembled into a mold according to the fiber architecture. The SEBS cladding, CPE electrodes (1.4 mm thick)., and piezoelectric composite layer (600 µm) were consolidated using a hot press at 100°C. The preform was drawn in a three-zone vertical tube furnace with a top-zone temperature of 120°C, a middle-zone temperature of 252°C, and a bottom-zone temperature of 80°C. CPE is a typical conductive thermoplastic polymeric electrode used in thermally drawn fibers. Compared to SEBS, CPE exhibits a lower viscosity and thereby undergoes a stable flow. On the other hand, its viscosity is higher than that of the piezocomposite, which delays the onset of capillary instability of the molten piezocomposite during the draw. CPE exhibits a conductivity of ~2 S/m, enabling transverse electronic transport. During the drawing process, 50 µm copper microwires (50 µm, Goodfellow, UK) with a conductivity of ~10^7 S/m do not undergo thermoplastic deformation but are fed into two empty channels in the CPE, and this convergence technique results in fibers containing four wires that are fully embedded in the CPE layers leading to axial electron transport along the fiber length. The fiber dimensions are monitored with laser-micrometers and the cross-section dimensions of the fiber are scaled down 20x compared to those of the preform. A detailed protocol of the acoustic fiber design and fabrication is elaborated in the **Supplementary Note 1** of the Supplementary Information.

The oscillatory shear rheology characterization

The oscillatory shear rheology characterization was carried out on a TA Instruments AR 2000 Rheometer. For rheological characterization, the polymer plates (1500-µm thick) were heated from 50 to 220 °C at 1 °C/min. The test was done in the oscillatory mode with an angular frequency of 1 rad/s and an oscillation strain of 1%.

X-ray Diffraction Characterization

Wide-angle and small-angle X-ray scattering characterizations were performed at the Massachusetts Institute of Technology (MIT) Center for Materials Science and Engineering (CMSE) X-ray Diffraction Shared Experimental Facility on a SAXSLAB system. Cu Kα1 X-rays of wavelength 1.5409 Å was produced by the Rigaku 002 microfocus X-ray source. Osmic staggered parabolic multilayer optics focused the beam crossover at the second pinhole. Two sets of JJ X-ray jaw collimation slits with diameters of 0.45 mm and 0.2 mm, respectively, were used to define the beam. The system was calibrated using silver behenate as a standard. The piezocomposite samples harvested from the fiber were directly fixed on the holes of the standard sample plate of the facility.

Piezoelectric charge coefficient d_{31} measurement

Rectangular-shaped gold (10 nm) electrodes were coated on both sides of the sample, using a Q300TD sputter coater (Quorum Technologies, Ltd., U.K.). The electrode length and width were measured using an optical microscope. The d_{31} measurement setup is shown in **Supplementary Fig. 6**. The d_{31} values with different dynamic stress values were measured by manually applying and removing a weight (1 ~ 200 g) at the end of the fiber. A quartz force sensor (model 208C01, PCB Piezotronics, Depew, NY, U.S.A.) was used to monitor the force applied on the fiber. A preforce of 10 g (0.098 N) was applied to keep the strain in the vertical direction. The generated charge was monitored using a Keithley 617 electrometer (Beaverton, OR, U.S.A.). Through a data-acquisition card (NI USB-6002, National Instruments, U.S.A.), the whole system was operated by the LabView software.

3D acoustical-mechano-electro model (COMSOL Multiphysics)

A 3D acoustical-mechano-electro model (COMSOL Multiphysics) that couples acoustics, mechanics and electrostatics was developed to simulate the system. The validity of the model is demonstrated in the **Supplementary Note 8.** All the components of the fiber were included into the model, and the materials properties are summarized in **Supplementary Table 1**.

In the 3D simulation, the membrane was modeled with a 2D shell module because the membrane thickness is much smaller than the lateral size (8 cm x 8 cm). A 6.5 cm long fiber, containing the piezoelectric domain and electrodes, was placed on the membrane surface at the center. The whole structure was placed in an air domain with perfect matching boundary layers in the surroundings. A pre-defined background acoustic plane wave was perpendicularly incident onto the membrane side with the fiber and induced vibration in the fiber and the membrane. The vibration was converted to voltage variation by the piezoelectric material in the fiber. Therefore, four physics modules were applied to compute the relevant physical effects: the pressure acoustic module for the air domain, the shell module for the membrane, the solid mechanics module for the fiber, and the electrostatics module for the piezoelectric material and electrodes.

The type and size of the mesh varied on different parts of the model. The air background and the shell model of the membrane were meshed with free tetrahedral and triangular elements, respectively. The fiber was meshed by sweeping the transversal surface, which was meshed with free triangular elements, along the fiber axis. The maximum size of the elements was determined by iteratively reducing the maximum mesh size in simulations until the change in the output values of interest between two consecutive simulations was below 5% (**Supplementary Table 2**).

The output of the simulation included the voltage from the electrodes, stress, displacement, and acoustic pressure at various locations of the model. The simulation allowed us to vary the system settings computationally and conduct sensitivity analyses for various parameters.

Acoustic and Laser Vibrometry Characterization

In all cases, samples fixed in a frame (See detailed methods in **Supplementary Note 5** in the Supplementary Information) were placed 2 meters from the speaker. A signal generator was used to input the desired frequency and power to the speaker. A dB meter was placed to the side of the frame, in the same plane as the fiber, and the power of the signal generator was adjusted until the desired SPL was reached. The fiber was connected to a PCB which was connected to an oscilloscope that recorded the fiber's response. The sample holder (i.e. frame) was placed on 10 cm of acoustic-insulating foam on the floor of an acoustic studio. The speaker also was set on foam on the floor. The displacement and vibrational modal patterns of the fiber-on-membrane and the acoustic fabric in response to different frequencies was concurrently measured using a PSV-500 Scanning Vibrometer (Polytec, USA) while measuring the output voltage from the samples. FFT was performed on each voltage signal to determine the output voltage. All characterization was performed in an acoustically damped and isolated music practice room, as an approximation to an anechoic chamber.

Standalone fiber: The two ends of the 6.7 cm fiber were attached across from each other in a 6.7 cm x 6.7 cm aluminum frame clamped to stand in an upright position.

Fiber on Mylar: The Mylar (50 μm in thickness, 8 cm in length and 8 cm in width) ES301955, metallized on one side, Goodfellow, UK) was fastened in a square 8 cm aluminum frame clamped in the upright position. A metallized Mylar can more efficiently reflect the visible light and generate higher SNR (signal-to-noise ratio) data during the laser vibrometer measurements. The boundary condition was well controlled (See detailed methods in **Supplementary Note 5** in the Supplementary Information). The 6.7 cm acoustic fiber was placed on the Mylar membrane. The SEBS cladding exhibits sufficient adhesion to the Mylar membrane, so the fiber sticks to the membrane without any adhesive. The entire fiber was in contact with the Mylar membrane as the SEBS cladding of the fiber is sticky.

Acoustic woven fabrics: The acoustic fiber was woven into the fabric. For acoustic characterization shown in Fig. 4, each fabric was clamped with well-controlled boundaries conditions (See detailed methods in **Supplementary Note 5** in the Supplementary Information). The fiber is ~6.7 cm long. The fabric size is 8 cm ×8 cm. The fabrics used for the demonstrations shown in Fig. 5 were integrated into shirts, so all fabrics were in a flexurally slack draped condition.

Weaving of Acoustic Fabrics

All fabrics were woven by hand on an 8-harness loom. A thin 100% cotton yarn (approximately 500 dtex, or 500 g per 10,000 m of yarn) was used for the warp. The warp density was 70 yarns per inch.

Two versions of a fabric were woven. The first Twaron/cotton fabric used 4 strands of 405 dtex Twaron yarn (2200, 1210 linear density, Teijin Aramid, Netherlands) as the weft, with a weft density of 48 yarns per inch. The second pure cotton fabric used 4 strands of 500 dtex cotton yarn as the weft, with a weft density of 44 yarns per inch. This slightly lower weft density was used to match the weight of the first fabric as closely as possible.

The weave structure of these fabrics is a variation of plainweave. Plainweave is the simplest weave structure, in which warp yarns are alternately raised over and lowered under each weft yarn. In this variation, an extra warp yarn is added next to every 6th yarn in the warp sequence. When weaving the fabric, these two yarns act as a pair, always raising or lowering together. When inserting the acoustic fiber, one yarn in the pair is raised while the other is lowered. This results in a series of warp yarns covering the fiber, spaced 2.5 mm apart, while the fabric under the fiber is woven in plainweave without extra warp yarns. This method produces very similar weave structures in the main fabric and at the fiber location. The dimension of the fabric shown in Fig. 4 is 8 cm (l) × 8 cm (w) × 0.46 mm (t).

Warp yarns on a loom are always under tension. When weaving the acoustic fiber into the fabric, the tension of the covering warp yarns was controlled so that the warp yarns slightly compressed the acoustic fiber while securing its position. The optimized compression force was measured to be 4.6 g. Two different methods were applicable for this purpose. For method 1, a group of yarns was inserted as a temporary weft in the same shed (configuration of raised warp yarns) as the fiber. These temporary wefts act as spacers between the warp yarns and the acoustic fiber: when they are removed from the fabric, the tension on these warp yarns is decreased. The second method of controlling warp yarn tension is on looms with two warp beams. Warp yarns are separated into two groups when preparing the loom for weaving, and each group is wound onto one beam. The tension on each group of yarns can be controlled independently by rotating the beam, which is held in place by a brake wheel.

Note that, a high compression force on the acoustic fiber impedes the fiber's ability to bend and the synergistically coupled vibration between the fabric and the fiber, resulting in lower performance (**Supplementary Fig. 29**).

Additional fabrics were woven and integrated into shirts shown in **Fig. 5**. These fabrics use the same cotton warp yarns and Twaron weft yarns, and a similar modified plainweave structure in which an extra warp yarn is added after every 3rd yarn. The same method of controlling warp tension when weaving the acoustic fiber was used.

The dimension of the acoustic shirt (twaron-weft/cotton-warp) shown in Supplementary Video 2 is 36 cm (l) × 23 cm (w) × 0.46 mm (t). The dimension of the woven fiber is 6.7 cm (l) × 0.1 cm (w) × 0.69 mm (t)). Thus, the volume fraction of the fiber occupying the fabric is only 0.097%.

Machine-wash Test

The fibers and the fabrics were placed in the protective delicate laundry bag and washed with a portable mini washing machine (PYLE PUCWM11). They experienced 10 washing cycles, and each cycle was 15 min ("cotton" wash mode) at the room temperature. No detergent was used during machine washing.

Data availability

All data supporting the findings of this study are available within the Article, Extended Data and Supplementary Information files. Representative source data for figures (Fig. 2f, Fig. 3, Fig. 4, Fig. 5b and c, Extended Data Fig.1c, Extended Data Fig. 2-5, Extended Data Fug. 6c, Extended Data Fig.7b, Extended Data Fig. 8, Supplementary Fig. 13 and 17) are publicly available at https://zenodo.org/record/5753073#.Ya6N-rdOmh8. Additional data are available from the corresponding authors upon reasonable request. Source data are provided with this paper.

Acknowledgements

Y.F. acknowledges the MIT MRSEC through the MRSEC Program of the National Science Foundation under award number DMR-1419807 and the US Army Research Laboratory and the US Army Research Office through the Institute for Soldier Nanotechnologies, under contract number W911NF-13-D-000, and Government of Israel, Ministry of Defense, Mission to the USA (No. 4440884397). L.Z acknowledges the National Science Foundation, Division of Materials Research, Polymers Program (DMR-2103196). G.N. acknowledges the National Science Foundation Graduate Research Fellowship Grant No. 1745302. C.M. and J.L. acknowledge the funding support from the University of Wisconsin Madison startup package and Wisconsin Alumni Research Foundation. The authors thank David Bono at DMSE, MIT for his contribution to the design of the circuit board, Henry Cheung at DMSE, MIT for setting up some experiments and Katherine Psaltos for drawing some schematics. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

Author contributions

W.Y. and Y.F. conceived and designed the project. Y.F. and J.J. supervised the project. W.Y. designed the fiber. W.Y., T.K. and G.N. fabricated fibers with inputs from A.S.. W.Y. performed electrical and material structure characterization. W.Y. developed the samples and methodology for the characterization of the spatial vibration patterns. W.Y. performed the laser vibrometry characterization and data analysis. W.Y. and G.N. performed acoustic characterization with contribution from J.C., J.W. and I.W.. J.A. and M.C. developed the 3D COMSOL model. M.C., G.N., W.Y. and J.L. performed simulation. G.R. measured the piezoelectric coefficient. G.R. and L.Z. analyzed the piezoelectric data. E.M. fabricated the fabrics with input from A.M.. G.N. performed demonstration of sound direction detection. W.Y. performed demonstration of acoustic communications and heart sound detection with input from G.L., J.C. and R.W.H.. W.Y., G.N. and Y.F. wrote the manuscript with input from all authors.

Ethics declarations

We have complied with all relevant ethical regulations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information is available for this paper.
Correspondence and requests for materials should be address to Y.F. (yoel@mit.edu)
Reprints and permissions information is available at www.nature.com/reprints.

Extended Data Legends

Extended Data Fig. 1 | Piezocomposite preparation and characterization. a, Schematic of the fabrication flow of the piezocomposite. The detailed description is shown in the Methods. The nanoparticles must be homogeneously distributed in the P(VDF-TrFE) matrix as aggregation can deteriorate energy conversion and causes fiber breakage during the draw. This requirement is achieved by using a planetary centrifugal mixing process that applies ultra-strong shearing forces to the composite suspension. **b,** SEM micrograph of a piezocomposite thin film fabricated without centrifuging treatment (left) and with centrifuging treatment (right). The inset in the left image highlights a severe agglomeration of $BaTiO_3$ nanoparticles while the inset in the right image presents a homogenous distribution of nanoparticles. **c,** Wide-angle X-ray scattering characterization of the hot-pressed as-cast composite and drawn P(VDF-TrFE)/$BaTiO_3$ fiber showing the β phase of P(VDF-TrFE) and tetragonal phase of the $BaTiO_3$ nanoparticles. The sharp equatorial arcs in the diffraction pattern of the drawn sample demonstrates that the thermal drawing process aligns the polymer chains along the draw direction. DD: fiber drawing direction; TD: fiber transverse direction. **d,** Bright-field TEM image of the $BaTiO_3$ nanoparticles harvested from the fiber. The inset shows the selected-area electron diffraction pattern from Transmission Electron Microscopy (TEM) characterization of a $BaTiO_3$ nanoparticle. Each nanoparticle is monocrystalline in the tetragonal phase. The particle size distribution is shown in the Supplementary Fig. 32. The TEM diffraction was performed using an FEI Tecni (G2 Spirit TWIN) under 120 kV.

Extended Data Fig. 2 | Hysteresis loops and poling method of the fiber. a, Electric polarization versus electric field hysteresis loops of a pure P(VDF-TrFE) fiber and fibers with varying weight percentages of $BaTiO_3$ nanoparticles (10, 20, 25 wt%). **b,** Step-wise poling method. The poling voltage is increased to 3300 V in 100 V steps. The schematics show the dipole orientation before and after the poling process.

Extended Data Fig. 3 | Optimization of the fiber design and fabrication. a, Temperature profile of the tower furnace. The draw temperature at the neck-down region is around 160 °C. The top surface of the furnance in the fiber draw tower was set to be the zero position. **b,** Rheological properties of the SEBS and piezocomposite. The oscillatory shear rheology of SEBS is slightly lower than that of the piezocomposite at the draw temperature. Thus, to ensure a smooth flow of the molten piezocomposite, two Cu wires instead of one wire are embedded in each of the two CPE electrodes. The tension applied on the four wires during the draw exerts compressive stress onto the molten piezocomposite in the neck-down region, thus preventing capillary breakup of the piezocomposite and creating highly uniform fibers (Extended Data Fig. 3c). **c,** Characterization of the fiber size for two different configurations. The 4-Cu wire configuration leads to a highly uniform fiber while the fiber size in the 2-Cu wire configuration fluctuates a lot because of the fluid instability.

Extended Data Fig. 4 | Stability of the electric property of the fiber. a, The ratio of the capacitance after and before the fiber was bent with a bending radius of 3.2, 2.0 and 1.2 cm for 1000 cycles respectively. To ensure a reliable bending radius, the fiber was mounted on a polymer substrate. After the first 1000-cycle test, the fiber was successively subject to the second and the third 1000-cycle tests. **b,** The ratio of the capacitance after and before the fiber was twisted with an angle of 45°, 180° and 540° for 1000 cycles respectively. All tests were done in a successively.

Extended Data Fig. 5 | Audible sound detection using the fiber-on-membrane. Time-dependent waveform of a clap (a), air blowing (b), leaves rustling (c) and birds chirping (d) detected using the fiber-on-membrane system.

Extended Data Fig. 6 | Stress and bending analysis of the fiber-on-Mylar. a, the bending/displacement of the middle x plane of the fiber at 300Hz (the deformation is scaled by a factor of 500) **b,** the bending/displacement of the middle y plane of the fiber (the deformation is scaled by a factor of 50000). **c,** the Cauchy stress distribution of the line in the middle of the piezocomposite along the fiber length. All simulation results were obtained from the 3D COMSOL model.

Extended Data Fig. 7 | Performance and modal patterns comparison between three fabrics where the piezoelectric fiber was woven directly. a, The setup used for the concurrent measurements. **b,** The frequency response and modal patterns of fabrics in three boundary conditions and tensions: a draping fabric with the top edge clamped where tension is supplied only by the fabric weight uniaxially (**c**), a fully clamped fabric where the only tension is supplied by fabric weight uniaxially (**d**), and a fully clamped fabric with externally imposed uniform biaxial tension (**e**). The uniform biaxial tension was achieved using the method elaborated in Supplementary Note 5. These measurements clearly show excellent electrical signals at audible frequency from all fabrics well above the noise regardless of the specifics of tension or boundary conditions. These measurements clearly establish and substantiate not only that the fabric is sensitivity under draping conditions but also that the electrical response emanates from nanometer amplitude displacements in the fabric which are captured by the fiber and are then transduced into electrical signals.

Extended Data Fig. 8 | The washability of the acoustic fabric. a, the snapshot photographs of the acoustic fabric being washed in a washing machine at room temperature. **b,** left: the constant capacitance with washing cycles. right: the voltage versus frequency of the acoustic fabric before it is washed and after it is washed for 10 cycles. Note that the cotton yarns in this fabric are grey while the cotton yarns shown in the Fig. 4 are green. The warp cotton yarn is a size 20/2 cotton with a set of 60 ends per inch and was threaded through a 12-dent reed. The weft yarn is a 1210 dtex Twaron yarn (Tejin Aramid, Arnhem, The Netherlands; tejinaramid.com). 4 strands of Twaron yarn (strands were not twisted together) were used in the weft direction. The size of the fabric is 17 cm, 17 cm by 1mm. The compression force the warp yarns applied to the fiber was measured to be 16.9 g using a force sensor (Taidacent, ZC-RP-C5ST-LF5-1024).

Extended Data Fig. 9 | Short-time Fourier transform spectrograms. The spectrograms of the audio used to drive the fabric emitter (top) and the audio detected by the fabric receiver (bottom) shown in **Fig. 5b**. Signals were sampled at 50 kHz, and data is shown from 20 Hz to 10 kHz in each case. A time window of 5 ms and overlap percentage of 20% was used to produce the spectrograms.

Extended Data Table 1 | Comparison of direct d_{31} piezoelectric coefficient between thermally-drawn P(VDF-TrFE)/BTO fiber and the state-of-the-art PVDF-based materials.