

Solution-processable n-type conducting polymer smart textiles for multifunctional wearable electronics

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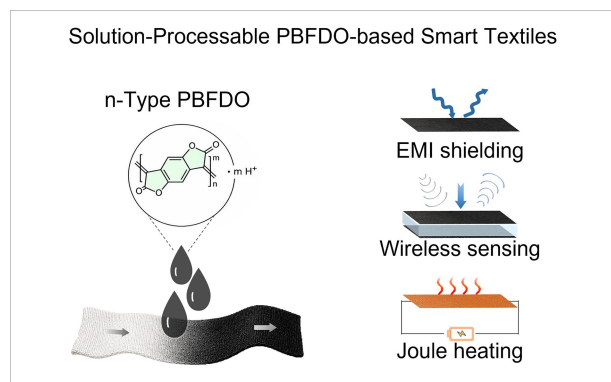
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A solution-processed PBFDO conductive textile is fabricated by combining PDA interfacial modification with WPU encapsulation on cotton fabric. The obtained WPCPF exhibits high conductivity and stable performance during air exposure, washing, and bending, while enabling EMI shielding, wireless passive strain sensing, and Joule heating for multifunctional wearable electronics.

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ABSTRACT: Multifunctional conductive textiles are essential components of emerging wearable electronic systems. However, simultaneously achieving high electrical conductivity, long-term environmental stability, textile-compatible manufacturing, and integrated device functions remains challenging. Here, we develop all solution-processed waterborne polyurethane/poly(benzodifurandione)/polydopamine/cotton fabric (WPPCF) conductive textiles by coating n-type poly(benzodifurandione) (PBFDO) onto commercial cotton fabric with interfacial modification and waterborne polyurethane encapsulation. WPPCF reaches a high conductivity of 454.51 S m⁻¹ with excellent air, washing and bending durability yielding an X-band electromagnetic interference (EMI) shielding effectiveness of 41.74 dB. Its tunable electromagnetic response enables a wireless passive compression strain sensor for dual-parameter remote strain readout through resonance-frequency shifts and amplitude variations. The textile also exhibits remarkable Joule heating, reaching 112.7 °C at 5 V under -25 °C ambient for low-temperature thermal management. This work provides a scalable wet-processing strategy and versatile platform for integrated intelligent wearable devices.

KEYWORDS: conductive textiles; poly(benzodifurandione); electromagnetic interference (EMI) shielding; electromagnetic functions; electromagnetic devices.

1 Introduction

Wearable electronics have witnessed prominent advancement and been widely deployed in mobile communication, physiological monitoring, athletic tracking, and intelligent home systems [1–5]. Conductive textiles stand as indispensable building blocks for wearable platforms, merging the intrinsic softness and conformability of conventional fabrics with functional electronic conductivity, thereby drawing considerable attention [6–10]. In real-service scenarios, wearables endure persistent mechanical distortion and variable ambient surroundings. Accordingly, conductive textiles are required to integrate superior electrical conductivity, mechanical pliability, environmental tolerance, and long-term operational durability [11,12]. Their industrial translation further hinges on facile, low-cost manufacturing routes compatible with large-area roll-to-roll fabrication [13–17].

Conductive textiles are commonly engineered by incorporating metallic fillers, conductive nanomaterials or conductive polymers into fibrous matrices. Metallic coatings deliver high electrical conductivity yet suffer severe mechanical incompatibility with textiles; poor interfacial adhesion leads to cracking and delamination upon cyclic bending or laundering. Moreover, vacuum deposition and multistep post-treatment hinder scalable mass production

[16–18]. Carbon nanotubes, graphene, and MXenes balance decent conductivity and lightweight features, but their practical fabrication is plagued by aggregation, nonuniform distribution, fragile fiber-matrix interfaces and prohibitive material expenses [19,20]. In comparison, conductive conjugated polymers exhibit superior mechanical compliance, low density, and intrinsic solution processability, facilitating conformal conductive coatings over textile fibers, rendering them compelling candidates for flexible conductive textiles [21–23].

Unfortunately, classic p-type conductive polymers including polyaniline, polypyrrole, and poly(3,4-ethylenedioxythiophene) rely heavily on reversible doping states to sustain conductivity [24–27]. Exposure to air, moisture, heat, and cyclic mechanical deformation readily induces de-doping, molecular conformational distortion and fracture of conductive percolation networks, resulting in a persistent bottleneck to synergistically achieve high conductivity, long-term stability, and scalable manufacture. Poly(benzodifurandione) (PBFDO) has recently emerged as a promising n-type conductive polymer [28–30]. Its planar conjugated backbone, deep electron affinity and in-situ stabilized highly n-doped backbone enable efficient charge transport and remarkable environmental stability. Benefiting from excellent solubility, uniform PBFDO

conductive layers can be deposited on complex fiber textures via scalable dip-coating. Preliminary explorations of PBFDO-based thermoelectric fibers and coated yarns have validated its great potential for fiber-based electronics [31,32]. However, rational interfacial engineering and percolated conductive-network construction of PBFDO within intact porous fabrics remain largely underexplored. In addition, the integration of PBFDO's conductive merits into unified textile platforms for concurrent electromagnetic interference shielding, wireless strain sensing and subzero-temperature thermal regulation has yet to be demonstrated.

Herein, we report a fully solution-processed multifunctional conductive cotton textile based on n-type PBFDO. A polydopamine pre-modification was implemented on microfibers to homogenize PBFDO deposition and strengthen fiber-polymer interfacial bonding. Sequential dip-coating builds continuous interconnected PBFDO conductive percolation networks, followed by waterborne polyurethane encapsulation to reinforce mechanical and environmental durability. The resulting textile preserves the inherent softness and deformability of cotton fabric while achieving an electrical conductivity of 454.51 S m^{-1} and a total electromagnetic interference (EMI) shielding effectiveness of 41.74 dB. Leveraging its tunable electromagnetic response, we construct a sandwich-structured passive strain sensor that realizes noncontact dual-parameter strain detection via resonance-frequency drift and S_{11} signal amplitude variation. The textile also delivers steady Joule-heating under both ambient and low-temperature conditions indicating low-temperature thermal management applications.

2 Experimental

2.1 Materials

Plain-woven cotton fabric was purchased from Zhejiang Kaida Fabric Co., Ltd. Potassium hydroxide (KOH, 99%), dopamine hydrochloride (98%), and tris (hydroxymethyl) aminomethane (Tris, 99%) were obtained from Aladdin. Hydrochloric acid (HCl, analytical reagent grade) was purchased from Sinopharm Chemical Reagent Co., Ltd. A PBFDO dispersion in N, N-dimethylacetamide (DMAc, 10 mg mL⁻¹) was supplied by Jurong Optoelectronic Materials Technology Co., Ltd. Waterborne polyurethane (WPU, 40 wt% solids), ferrocene (99%), and tetrabutylammonium hexafluorophosphate (TBAPF₆, 98%) were purchased from Shanghai Macklin Biochemical Co., Ltd. All materials and reagents were used as received without further purification.

2.2 Methods

2.2.1 Preparation of the Conductive Textiles

Plain-woven cotton fabric was immersed in a 0.1 wt% KOH aqueous solution and stirred at 80 °C for 1 h. It was then washed three times with deionized water and anhydrous ethanol, followed by drying at 60 °C for 24 h to yield pretreated cotton fabric (CF). CF was immersed in a Tris-HCl buffer solution containing dopamine hydrochloride (1 mg mL⁻¹, pH 8.6, 1 M Tris) for 12 h. After identical washing and drying procedures, polydopamine-coated fabric (PCF) was obtained. PCF underwent sequential dip-coating in a PBFDO/DMAc dispersion (5 mg mL⁻¹) for 1 min per cycle. After each dip-coating cycle, the fabric was oven-dried at 80

°C for 24 h to remove residual solvent, generating PPCF. The PPCF was further immersed in a 5 wt% WPU dispersion for 1 min and dried at 60 °C for 24 h. According to the number of PBFDO dip-coating cycles, the final samples were denoted as WPPCF-1, WPPCF-2, WPPCF-4, WPPCF-6, WPPCF-8, and WPPCF-10. Unless otherwise specified, WPPCF is considered as WPPCF-10.

2.2.2 Characterization and Performance Measurements

The surface morphology of the samples was examined by field-emission scanning electron microscopy (FESEM, Ultra 55, Zeiss, Germany). UV-vis absorption spectra were recorded using a UV-vis spectrophotometer (Shimadzu, UV-3600i Plus, Japan). Raman spectra were collected using an inVia Qontor Raman microscope (Renishaw, UK) with 532 nm laser excitation. Fourier-transform infrared spectra were acquired using an FTIR spectrometer (IRTracer-100, Shimadzu, Japan). Surface elemental compositions and chemical states were analyzed by X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Fisher Scientific, USA), with the binding-energy scale calibrated against the C 1s signal. Surface water contact angle tests of the samples were carried out using a contact angle measuring instrument (OCA 20, Dataphysics, Germany) at room temperature. Soft X-ray absorption spectroscopy (sXAS) was performed at the BL10B beamline of the National Synchrotron Radiation Laboratory, Hefei, where the N K-edge and O K-edge spectra were collected.

Uniaxial tensile tests were conducted using a universal testing machine (UTM4103, SUNS, China) at a crosshead speed of 50 mm min⁻¹. The electrical conductivity was measured by the four-point probe method using an RST-8 four-point probe tester (Guangzhou Four-Probe Technology Co., Ltd., China). The conductivity of all samples was measured in parallel 5 times and the average value was taken (Table S1-S5). EMI shielding performance was evaluated by the waveguide method using a PNA microwave network analyzer (N5227A, Keysight Technologies, USA). For Joule-heating measurements, the textile samples were clamped between two electrodes and powered using a programmable linear DC power supply (eTM-L305SPL, eTOMMENS, China). The surface temperature was monitored using a thermocouple thermometer (CT06A, SMRF-T, China), while infrared thermal images were captured using an infrared camera (Short Cam Mini, LC-AS21 Mini, Launch Digital, China). Ambient-temperature measurements were conducted under laboratory conditions, whereas low-temperature tests were performed in the freezer compartment of a chest freezer (BD-100KEM(E), Midea, China).

2.2.3 Electromagnetic simulation

The structure and electromagnetic response of the wireless strain sensor were simulated using ANSYS HFSS 2023 R1. A periodic single cell model was constructed, consisting of an upper low conductivity WPPCF-1 layer, a silicone rubber spacer, and a lower high conductivity WPPCF-10 layer. Each textile layer was represented by an equivalent plain-woven geometry with crimped warp and weft yarns. The unit cell size was 0.53 mm × 0.53 mm, the yarn pitch was 0.265 mm, the equivalent yarn diameter was 0.15 mm, and the yarn crimp amplitude was 0.08 mm, giving

an equivalent single fabric thickness of 0.31 mm. The spacer thickness d was varied to simulate compressive deformation. Detailed geometric and electromagnetic parameters are provided in Fig. S1 and Table S6. The electrical

conductivities of the upper and lower textile layers were set to that of WPPCF-1 and WPPCF-10, respectively. The relative permittivity, dielectric

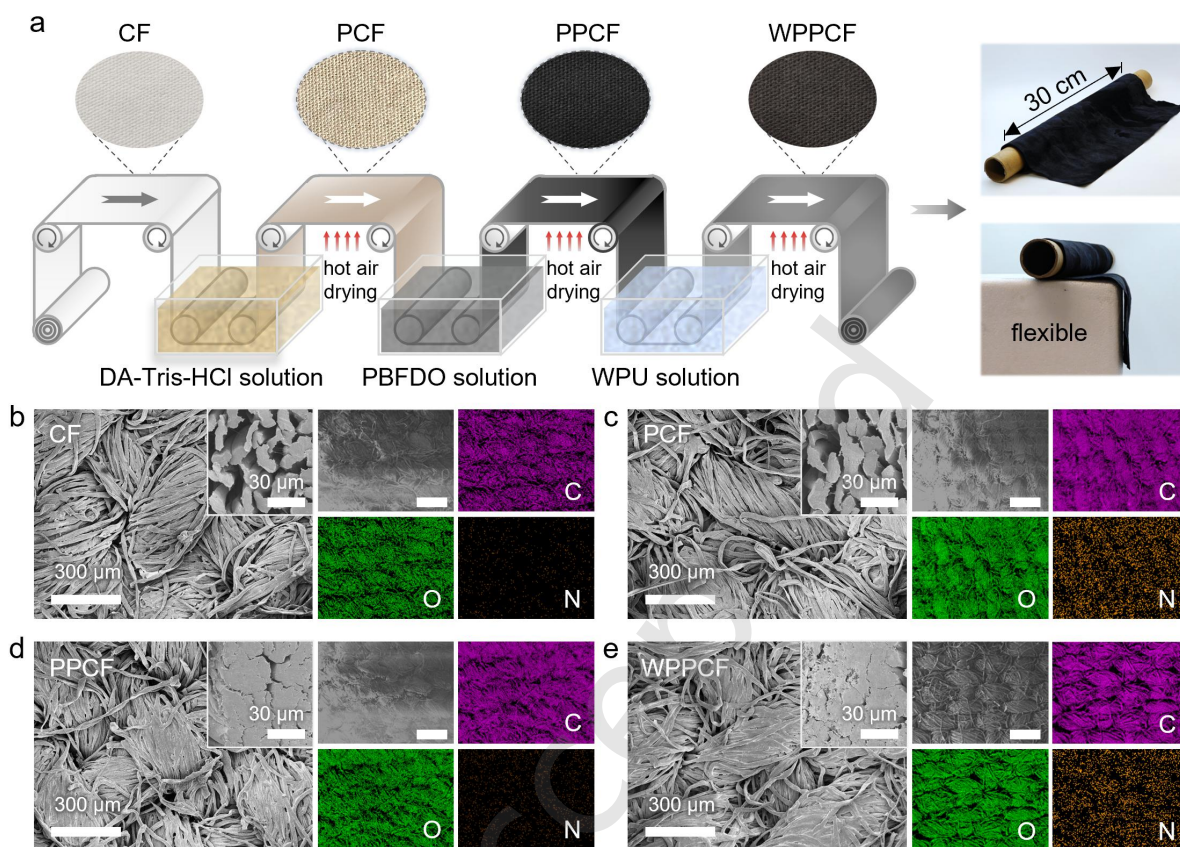


Figure 1 (a) Schematic illustration of the scalable all-solution fabrication route for WPPCF. The photographic insets show the appearance of the fabrics. The SEM images and EDS mapping of (b) CF, (c) PCF, (d) PPCF and (e) WPPCF (insert showing cross-sectional SEM images of the samples).

loss tangent, and electrical conductivity of silicone rubber were set to 2.8, 0.02, and $10^{-12} \text{ S m}^{-1}$, respectively. Primary–Secondary periodic boundary conditions were applied in the in-plane directions, and Floquet ports were assigned to the upper and lower boundaries to simulate normally incident electromagnetic waves. The fundamental mode of the first Floquet port was excited with a normalized power of 1 W. Adaptive meshing was performed at 10 GHz, and the reflection coefficient S_{11} and transmission coefficient S_{21} were calculated over the frequency range of 8–12.4 GHz.

3 Results and discussion

Fig. 1(a) schematically depicts the scalable all-solution fabrication route toward WPPCF. CF was first immersed in a Tris–HCl buffer containing dopamine, allowing an interfacial PDA coating on the fabric through oxidative polymerization and yielding PCF. Subsequently, PCF was immersed in a PBFDO dispersion in DMAc to obtain PPCF. Finally, PPCF was encapsulated by immersion in a WPU dispersion to obtain WPPCF. As shown in the inset photographs, with the sequential introduction of PDA, PBFDO, and WPU, the fabric color changed from white to brown and ultimately black. WPPCF retained the flexibility of the original cotton fabric and could be readily draped, while also undergoing small-radius bending and rolling deformation (Fig. S2). The stress-

strain curves in Fig. S3 confirm that multilayer coating treatment does not compromise the mechanical properties of the fabric. Notably, WPPCF delivers improved tensile strength relative to pristine CF, which may be attributed to strengthened inter-fiber bonding and reinforcement at fiber junctions.

SEM images reveal the evolution of the surface morphology and cross-sectional structure during each step. The pristine CF presents interwoven cotton fiber bundles with relatively smooth surfaces, and distinct inter-yarn voids can be clearly observed in the cross-sectional view (Fig. 1(b)). EDS mapping indicates that CF is composed mainly of C and O elements, consistent with the elemental composition of cellulose, with no discernible N signal. After PDA modification, PCF well preserves the intrinsic woven texture of cotton fabric, suggesting the formation of a thin and uniform PDA layer (Fig. 1(c)). The emerging N signal in EDS spectra further confirms the successful immobilization of nitrogen-containing PDA layer. Control experiments show that PDA modification improves the wettability of cotton fabric and facilitates more uniform and efficient PBFDO deposition during dip-coating (Fig. S4–S6). After PBFDO deposition, PPCF maintains its macroscopic woven structure, whereas the cross-sectional SEM images verify that PBFDO effectively fills and bridges inter-fiber voids (Fig. 1(d)). The

distinctly attenuated N signal is attributed to the thick PBFDO overlayer, which shields the underlying PDA elemental signal. Considering that DMAc contains nitrogen whereas PBFDO is nitrogen-free, the absence of an obvious additional N signal in PPCF further suggests that no

appreciable DMAc residue remained after drying. After WPU encapsulation, WPPCF exhibits a nearly identical morphology to PPCF, indicating that the thin WPU protective layer imposes negligible structural disturbance to the textile framework (Fig. 1(e)). The reappearance of a

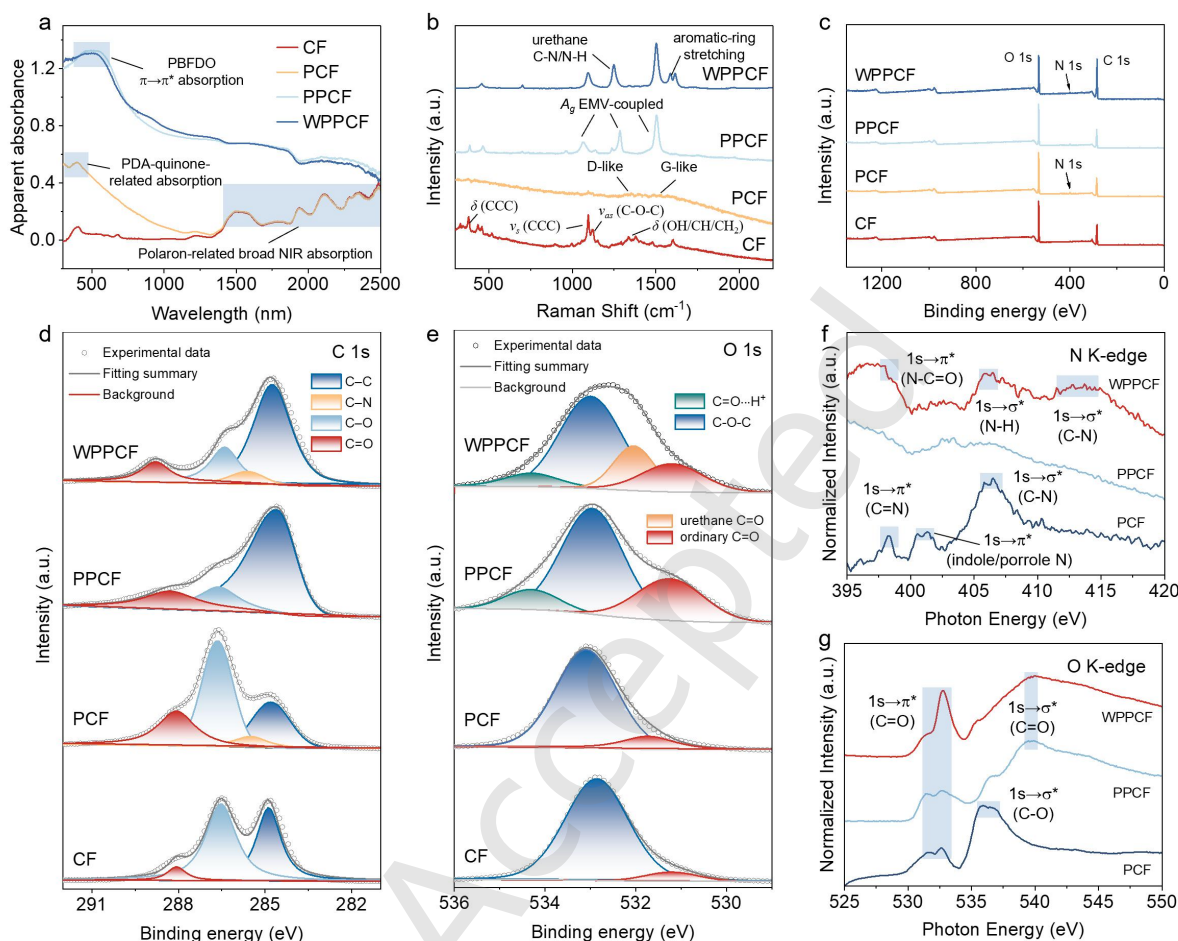


Figure 2 Spectroscopic characterization of CF, PCF, PPCF, and WPPCF. (a) UV-vis-NIR absorbance spectra. (b) Raman spectra. (c) XPS survey spectra. High-resolution of (d) C 1s and (e) O 1s XPS spectra with peak fitting. (f) N K-edge and (g) O K-edge soft X-ray absorption spectra.

pronounced N signal strongly corroborates the successful coating of urethane-based WPU. Multiple spectroscopic techniques were employed to characterize CF, PCF, PPCF, and WPPCF. As shown in Fig. 2(a), CF shows negligible UV-visible absorption [33]. In contrast, PCF delivers a broad absorption peak centered at approximately 396 nm, mainly associated with quinone-containing chromophores in PDA [34]. PPCF exhibits markedly enhanced broadband absorption spanning the ultraviolet-visible-near-infrared region, with a broad maximum at approximately 491 nm arising primarily from the high-energy π - π^* transition of the conjugated PBFDO backbone [35]. The continuous absorption extending into the near-infrared region was consistent with polaron-related electronic states in highly n-doped PBFDO [36]. After WPU encapsulation, WPPCF retains the PBFDO-dominated broadband absorption feature, with a slight red-shift of the absorption peak to approximately 505 nm. This minor spectral variation stems from the altered local dielectric environment and light-scattering behavior induced by the WPU coating [37].

Raman spectra further validate the successful sequential functionalization of textile substrates (Fig. 2(b)). Pristine CF

presents characteristic peaks of cellulose at 379, 1095, 1122, 1338 and 1380 cm^{-1} , corresponding to ring skeleton deformation ($\delta(\text{CCC})$), ring skeleton breathing vibration ($\nu_s(\text{CCC})$), asymmetric stretching of glycosidic bond ($\nu_s(\text{C-O-C})$) and vibrations of OH, CH and CH_2 groups ($\delta(\text{OH/CH/CH}_2)$), respectively [38]. After PDA modification, PCF displays broad D-like and G-like bands centered at 1350 and 1600 cm^{-1} , associated with the disordered aromatic structure and in-plane aromatic-ring vibrations of PDA [39]. For PPCF, a set of well-defined characteristic peaks belonging to PBFDO emerge, among which the prominent peaks at 1065, 1286, and 1504 cm^{-1} were assigned to Ag EMV-coupled modes [40]. After WPU encapsulation, the intrinsic fingerprint peaks of PBFDO are well preserved in WPPCF. Meanwhile, the new characteristic signals at approximately 1248 cm^{-1} and 1615 cm^{-1} appear in WPPCF spectra, which may be associated with coupled C-N stretching and N-H bending vibrations of the urethane groups, and aromatic-ring stretching of the WPU hard segments, respectively, further verifying the successful introduction of WPU protective layers [41].

The XPS survey spectra further confirm the stepwise

chemical composition evolution of the textiles. All samples exhibit predominant C and O signals, while weak N 1s signals are detected in PCF and WPPCF, which correspond to the introduction of PDA and WPU coatings, respectively (Fig. 2(c)). High-resolution C 1s spectra were further

deconvoluted to analyze surface chemical states (Fig. 2(d)). The fitted peaks of CF at 284.9, 286.5, and 288.1 eV were assigned to C–C, C–O, and C=O, respectively [42]. A new C–N component appeared at 285.5 eV in PCF, accompanied by an enhanced C=O signal

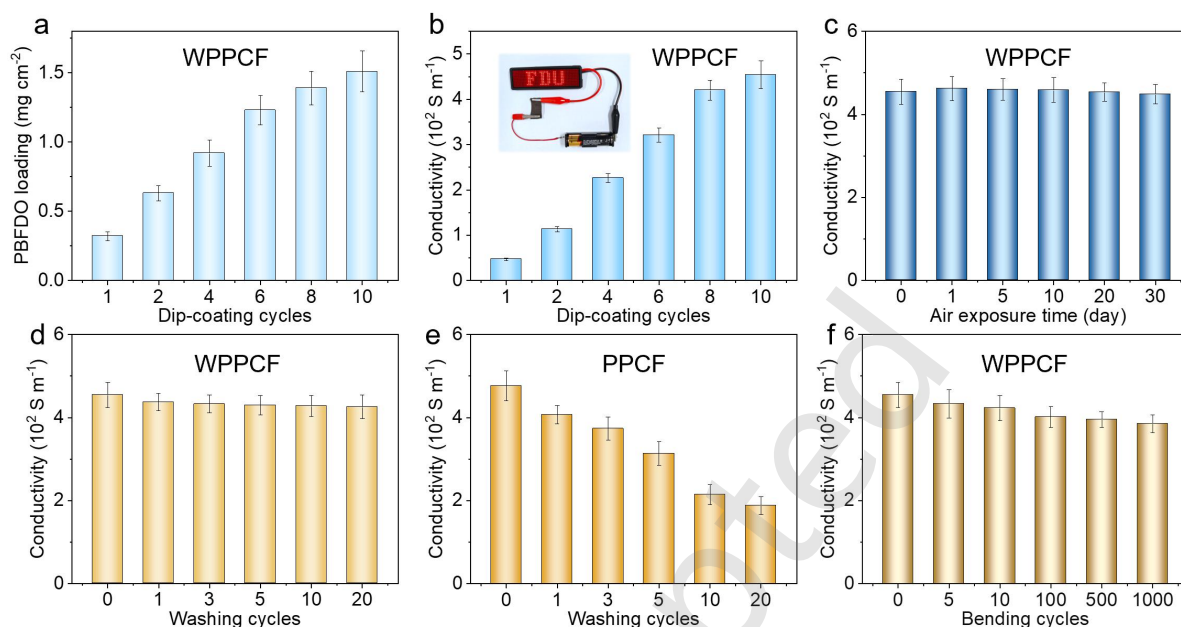


Figure 3 (a) PBFD loading mass of WPPCF at different dip-coating cycles. (b) Conductivity of WPPCF at different dip-coating cycles. (c) Conductivity during air exposure of WPPCF. Conductivity of (d) WPPCF and (e) PPCF after washing cycles. (f) Conductivity of WPPCF after repeated bending.

at 288.1 eV, in agreement with the incorporation of nitrogen-containing and quinone-like structures from PDA [43]. For PPCF, the pronounced increase in the conjugated C–C component at 284.6 eV indicates that the PBFD conjugated backbone dominated the surface signal [44]. The C–N component reappeared at 285.6 eV in WPPCF, consistent with the urethane-containing WPU overlayer [45]. Fig. 2(e) shows the high-resolution O 1s spectra. Both CF and PCF were dominated by the C–O component near 533.0 eV [46]. The minor carbonyl components at approximately 531.2–531.4 eV may originate from oxidized groups or processing residues on the cotton fibers and quinone-like structures from PDA [47]. For PPCF, the fitted peak at 531.2 eV was assigned to non-protonated carbonyl oxygen (ordinary C=O), the component at 532.9 eV mainly arose from the furan-ring oxygen of PBFD and C–O environments in the substrate. The high binding energy component at 534.3 eV was attributed to carbonyl oxygen interacting with charge-compensating protons (C=O⋯H⁺). This assignment is supported by the O 1s XPS spectrum of the neat PBFD film (Fig. S7), in which a similar C=O⋯H⁺ component is observed. Based on the carbonyl-related peak areas and the two carbonyl groups in each PBFD repeat unit, the proton-compensated doping ratio of PBFD was estimated to be 74.1% per repeat unit [48]. As for WPPCF, an additional urethane carbonyl (urethane C=O) component appeared at approximately 532.0 eV, consistent with the formation of the WPU coating [49].

Figs. 2(f) and 2(g) present the soft X-ray absorption spectra. The N K-edge spectrum of PCF exhibited resonances at around 398.2, 401.3, and 406.3 eV. The first resonance was

assigned to the N 1s→π* (C=N) transition of imine or quinone-imine structures, whereas the feature at 401.3 eV was associated with π* states of indole/pyrrole N species in PDA. The broad resonance near 406.3 eV originated primarily from C–N related σ* states [50]. Given the nitrogen-free molecular structure of PBFD, PPCF exhibits no discernible N K-edge resonances and the trace residual N signal likely originated from the underlying PDA layer. After WPU encapsulation, additional features appeared at approximately 402.9, 406.1, and 413.7 eV, which were associated with the π* (N–C=O), σ* (N–H), and σ* (C–N) states of the urethane groups, respectively [51]. In the O K-edge spectra, the resonances at approximately 532.4–532.8 eV were assigned to O 1s→π* (C=O) transitions. The broad feature of PCF near 536.1 eV mainly originated from C–O related σ* states in the catechol-containing PDA structure [52]. The higher-energy bands of PPCF and WPPCF at approximately 539.7–540.0 eV were attributed to σ* states associated with the C=O environments of PBFD and WPU [53]. FTIR spectra were further collected to support the chemical-composition evolution during the stepwise fabrication process (Fig. S8). The characteristic cellulose bands are retained in CF and PCF, while PBFD deposition and WPU encapsulation introduce additional carbonyl/conjugated-backbone and urethane-related absorptions, respectively, further confirming the successful construction of WPPCF.

The loading evolution of PBFD with increasing dip-coating cycles was systematically investigated. As the number of dip-coating cycles increased, the PBFD loading amount continuously increased and reached 1.51 mg cm⁻² after 10

cycles (Fig. 3(a)). With increasing PBFDO loading, the overall electrical conductivity of the fabric exhibited a continuous enhancement. As shown in Fig. 3(b), the conductivity of WPPCF increased continuously with the number of PBFDO dip-coating cycles. As the number of coating cycles increases from 1 to 10, the conductivity rises substantially from 46.77

to 454.51 S m^{-1} . This enhancement originates from the gradual accumulation of PBFDO loading, which facilitates the formation of denser, more continuous and interconnected conductive networks throughout the textile framework (Fig. S9). For comparison, the neat PBFDO film exhibited a much higher conductivity (Table S7), confirming the high intrinsic

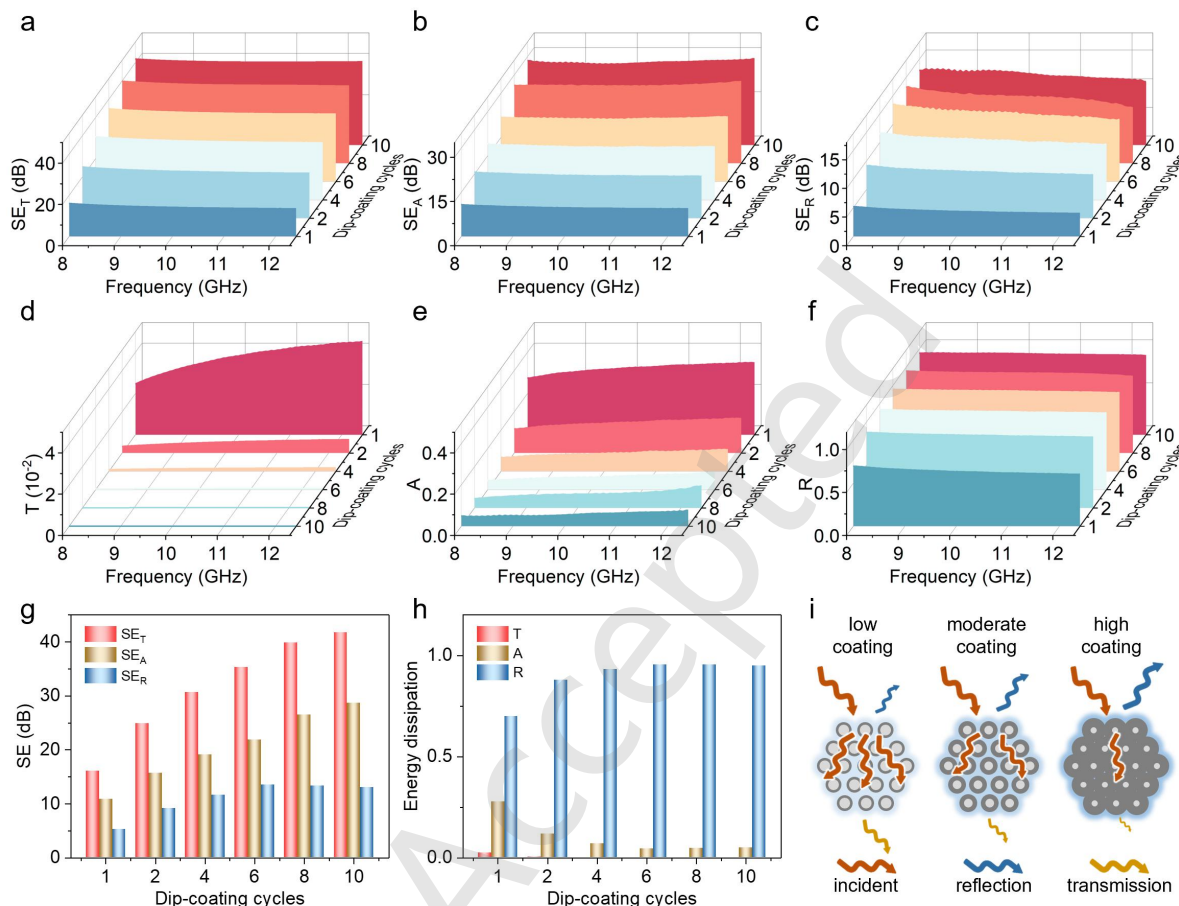


Figure 4 (a) SE_T , (b) SE_A , (c) SE_R , (d) T , (e) A , (f) R of WPPCF with different PBFDO dip-coating cycles. Histograms of (g) $SE_T/SE_A/SE_R$, and (h) $T/A/R$ of WPPCF. (i) Schematic diagram of EMI shielding mechanism of WPPCF with different PBFDO loading amounts.

charge-transport capability of PBFDO. The lower fabric level conductivity of WPPCF is therefore mainly associated with the porous textile architecture, inter fiber contact resistance, and tortuous conductive pathways rather than the intrinsic conductivity limitation of PBFDO. The partially ordered packing of neat PBFDO, as confirmed by XRD, is beneficial for interchain charge transport and supports its high intrinsic conductivity (Fig. S10). As demonstrated in the inset, WPPCF could serve as a flexible electrical lead to illuminate an “FDU” sign, visually confirming its efficient charge-transport capability. Preliminary experiments on twill nylon fabric further suggest that this solution-based PBFDO impregnation strategy can be extended to other textile substrates, as evidenced by retained woven morphology, increased conductivity, and enhanced EMI shielding after repeated dip-coating (Fig. S11, S12). The optimized WPPCF also achieves exceptional long-term ambient stability. As shown in Fig. 3(c), after 30 days of exposure to ambient air, its conductivity slightly decreases from 454.51 to 448.31 S m^{-1} , maintaining a high retention rate of 98.7 %. No obvious deterioration in conductivity was observed throughout the exposure period, confirming the robust structure and

electrical stability of the WPPCF conductive network. Such excellent environmental tolerance benefits from the intrinsically stable n-doped state of PBFDO and the barrier protection of the outer WPU coating, which suppresses the penetration of ambient moisture and oxygen.

The coating durability of WPPCF was further assessed via repeated washing treatment. The textile samples were immersed in surfactant aqueous solution and subjected to either simulated machine washing by mechanical stirring at 200 rpm for 45 min per cycle. As shown in Fig. 3(d), WPPCF retains a conductivity of 425.76 S m^{-1} after 20 washing cycles, corresponding to a high retention of 93.7 %. In contrast, PPCF without WPU encapsulation suffered from severe electric attenuation under identical washing conditions (Fig. 3(e)), with its conductivity dropping sharply to 187.63 S m^{-1} and a retention rate of only 39.4 %. The substantial conductivity loss of PPCF may arise from partial detachment of the PBFDO coating during washing, together with disruption of the conductive network caused by water-induced swelling of the cotton fibers. By comparison, the WPU encapsulation layer not only immobilized PBFDO on the fiber surface but also suppressed fiber swelling to some

extent, thereby preserving the continuity of the conductive network. These structural evolutions are further validated by SEM observations of washed samples (Fig. S13). Apart from washing robustness, WPPCF also possesses outstanding mechanical bending durability. As shown in Fig. 3(f), the conductivity of WPPCF decreases only gradually to 384.73 S m^{-1} after 1000 consecutive bending cycles

retaining 84.6 % of its initial value. The slight conductivity decline may be associated with the formation of localized microcracks in the coating and changes in inter-fiber contact states. Nevertheless, the overall textile microstructure remains well preserved after cyclic bending (Fig. S14), further confirming the excellent mechanical

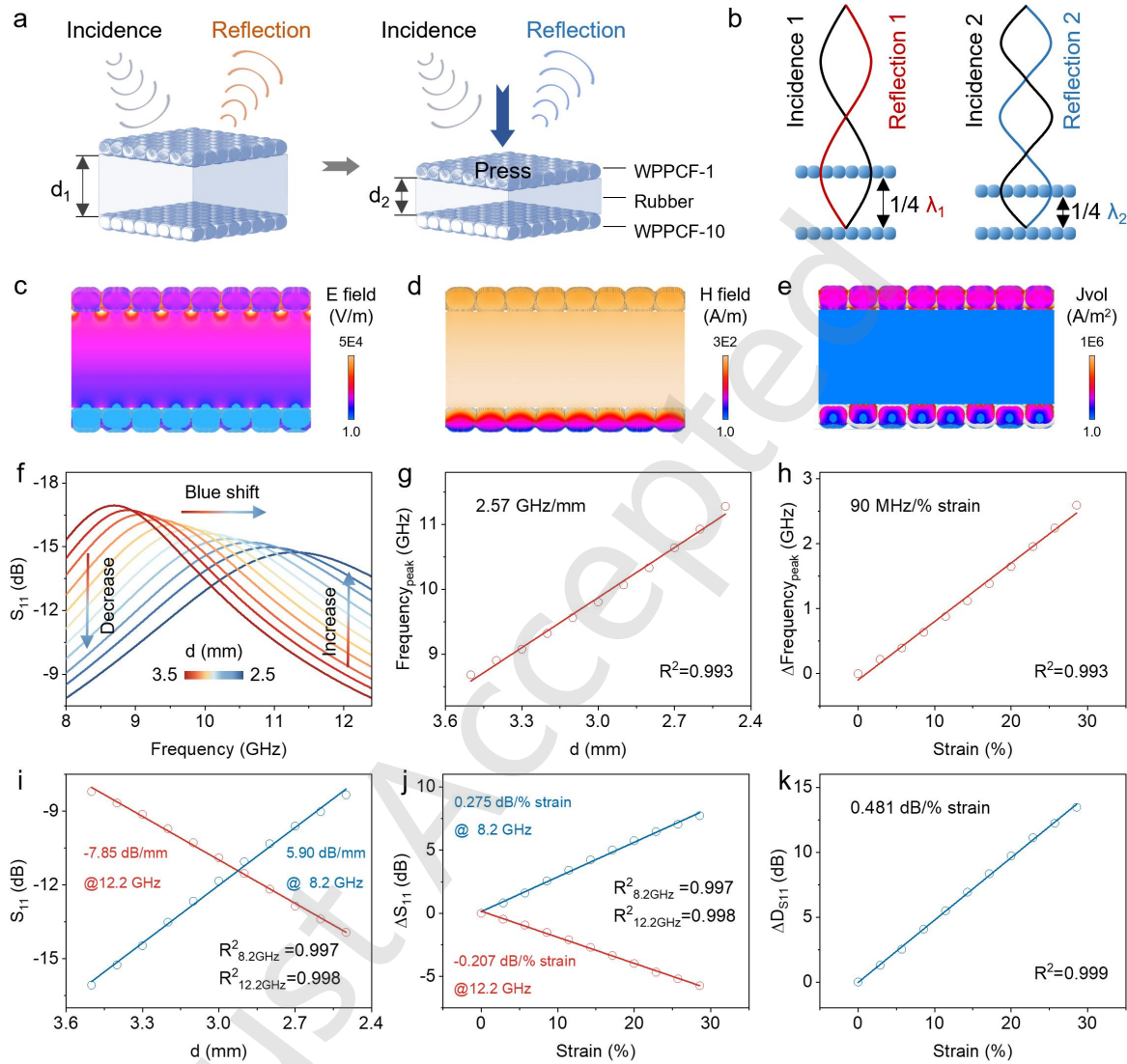


Figure 5 (a) Schematic illustration of the wireless strain sensor based on WPPCF (b) Schematic of the quarter-wavelength matching mechanism of WPPCF sensor. Simulated (c) electric-field, (d) magnetic-field, and (e) volume-current-density distributions. (f) Simulated S_{11} spectra at different spacer thicknesses d . (g) Dependence of the resonance frequency on d . (h) Resonance-frequency shift as a function of strain. (i) S_{11} values at 8.2 and 12.2 GHz as functions of d . (j) ΔS_{11} at the two monitoring frequencies with strain. (k) $\Delta D_{S_{11}}$ response as a function of strain.

adaptability and structural robustness of the WPPCF composite textile.

The high electrical conductivity of WPPCF endows it with efficient EMI shielding. As shown in Figs. 4(a-c), the total shielding effectiveness SET, absorption shielding effectiveness SEA, and reflection shielding effectiveness SER of all samples varied only slightly across the X-band, indicating stable broadband shielding capability. With the PBFDO dip-coating cycles increasing from 1 to 10, the maximum SE_T of WPPCF progressively rises from 16.07 to 41.74 dB, accompanied by continuous enhancements of SE_A (from 10.84 to 28.70 dB) and SE_R (from 5.22 to 13.05 dB)

(Fig. 4(g)). Fig. 4(d-f) further show the transmission coefficient (T), absorption coefficient (A), and reflection coefficient (R) of the different samples. Increasing PBFDO loading caused a continuous decrease in T from 2.47×10^{-2} to 6.70×10^{-5} , indicating that the optimized WPPCF-10 blocks more than 99.99% of incident electromagnetic waves. Meanwhile, the R rapidly increases from 0.6997 to ~ 0.95 and then gradually saturates at higher PBFDO loadings, whereas A monotonically decreases from 0.2756 to approximately 0.0495 (Fig. 4(h)). The loading-dependent shielding mechanism is schematically illustrated in Fig. 4(i). At low PBFDO loading, the incomplete surface coverage

leaves abundant interstitial pores and penetrating channels within the textile. Incident electromagnetic waves can easily propagate through the textile and undergo multiple scattering and interfacial reflection, resulting in a relatively high fraction of absorbed incident energy while still allowing partial transmission. With increased PBFDO deposition, isolated conductive regions on the fiber surfaces gradually interconnected to form a more continuous conductive

network. This structural evolution suppresses wave absorption while significantly enhancing surface reflection. At sufficiently high PBFDO loading, the densely conductive layer generates prominent impedance mismatch between the textile surface and free space, enabling most incident electromagnetic waves to be reflected at the surface, with nearly zero transmitted energy.

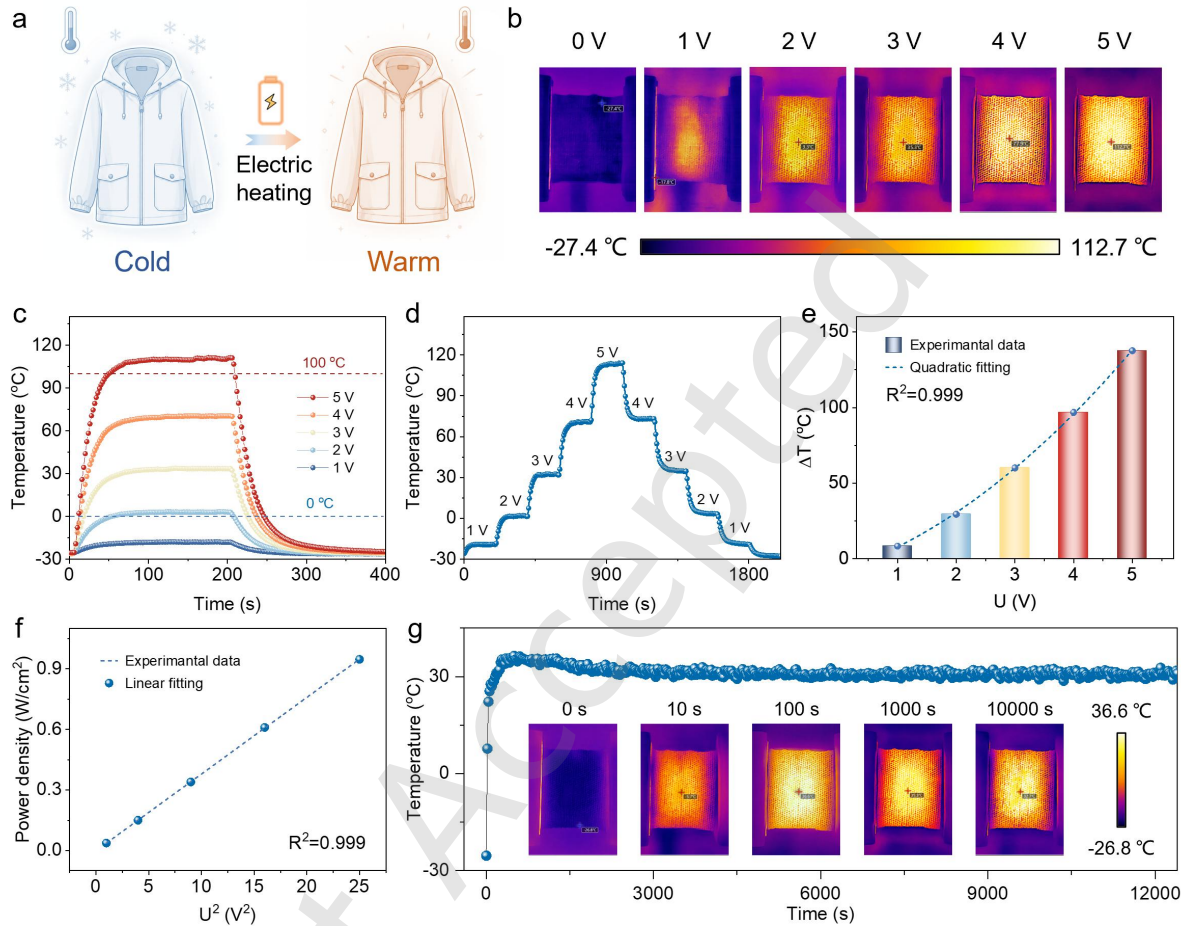


Figure 6 (a) Schematic illustration of wearable electric heating under cold conditions. (b) Infrared thermal images under applied voltages from 0 to 5 V. (c) Temperature-time profiles at different voltages. (d) Stepwise heating and cooling response under cyclic voltage switching between 1 and 5 V. (e) Equilibrium temperature rise (ΔT) as a function of applied voltage and the corresponding quadratic fitting curve. (f) Linear relationship between the power density and U^2 . (g) Long-term Joule-heating stability under subzero conditions, with infrared images recorded.

Leveraging the tunable electromagnetic response of WPPCF, a sandwich-structured wireless passive compression strain sensor was further designed. Conventional strain sensors typically require wired signal transmission, which restricts device miniaturization, system integration, and practical operation in harsh environments [56-58]. In comparison, this as-designed sensor enables non-contact strain readout through remote acquisition of reflected electromagnetic signals. As shown in Fig. 5(a), the sensor consists of an upper WPPCF-1 layer, a flexible rubber spacer, and a lower WPPCF-10 layer. Upon electromagnetic irradiation, compression-induced changes in the interlayer spacing alter the reflection parameter S_{11} , allowing the strain signal to be monitored wirelessly. The operating mechanism can be explained by quarter-wavelength phase matching (Fig. 5b). When the thickness between the two conductive layers satisfies the quarter-wavelength condition, the reflected

waves undergo destructive interference, producing a distinct resonance dip in the S_{11} . Compression shortens the effective propagation path of the electromagnetic wave. Consequently, the matched wavelength decreases, causing the resonance frequency to shift, accompanied by a change in resonance intensity.

Electromagnetic field simulation further reveals the underlying sensing mechanism (Figs. 5(c-e)). The electric field is mainly distributed within the rubber spacer and near its interfaces with the conductive textiles, whereas the stronger magnetic field and volume current density are concentrated around the lower WPPCF-10 layer. These results indicate that interlayer electromagnetic coupling and induced currents in the conductive textiles determine the resonance response of the device. Fig. 5(f) shows the simulated S_{11} spectra at different interlayer spacings (d). As d decreased from 3.5 to 2.5 mm, the resonance dip

continuously blue-shifted from approximately 8.68 to 11.28 GHz. The resonance frequency exhibited a good linear relationship with the interlayer spacing, with a sensitivity of 2.57 GHz/mm (Fig. 5(g)). After converting the spacing change into compressive strain, the resonance-frequency shift also showed a good linear dependence on strain, with a frequency sensitivity of 90 MHz/% (Fig. 5(h)). These results demonstrate that compressive strain can be quantitatively determined by tracking the resonance frequency.

In addition to the resonance-frequency shift, the S_{11} amplitude at fixed frequencies can also be used as a sensing signal. As shown in Fig. 5(i) and 5(j), with increasing compressive strain, S_{11} at 8.2 GHz increased from approximately -16.07 to -8.33 dB, corresponding to a sensitivity of 0.275 dB/%. In contrast, S_{11} at 12.2 GHz decreased from approximately -8.20 to -13.93 dB, with a sensitivity of -0.207 dB/%. Further, a dual-frequency differential response (ΔD_{S11}) was defined as Eq. (1):

$$\Delta D_{S11} = \Delta S_{11, 8.2 \text{ GHz}} - \Delta S_{11, 12.2 \text{ GHz}} \quad (1)$$

As shown in Fig. 5(k), the ΔD_{S11} increases linearly with strain, yielding a sensitivity of 0.481 dB/%. Compared with single-frequency amplitude readout, the dual-frequency differential strategy produces a larger signal variation and improves the sensitivity of wireless strain detection.

The high electrical conductivity of WPPCF endows it with stable Joule-heating capability. As illustrated in Fig. 6(a), the textile converts electrical energy into heat under an applied voltage, enabling personal thermal management in low-temperature environments. Fig. 6(b) shows infrared thermal images of WPPCF under applied voltages of 0–5 V at an ambient temperature of approximately -25 °C. The temperature increased with increasing voltage, reaching a maximum of 112.7 °C at 5 V. Fig. 6(c) presents the temperature–time curves under different applied voltages. WPPCF heated rapidly after energization and reached a steady state within a short period. As the voltage increased from 1 to 5 V, the temperature rose progressively. As shown in Fig. 6(d), when the voltage was increased and decreased stepwise between 1 and 5 V, the textile responded rapidly and produced well-defined temperature plateaus, demonstrating good electrothermal tunability. Moreover, fitting the equilibrium temperatures at different voltages revealed a clear quadratic dependence of the heating temperature on the applied voltage, consistent with the voltage-dependent Joule-heating behavior (Fig. 6(e)). The power density shows a strong linear relationship with U^2 (Fig. 6(f)), confirming that the heating behavior followed Joule's law. WPPCF also exhibits good long-term operating stability under low-temperature conditions. As shown in Fig. 6(g), during continuous operation for 10,000 s at a constant voltage, the textile maintains a stable temperature of approximately 36.6 °C without obvious thermal runaway. This result indicates its potential to provide a stable heat output near a comfortable body temperature in cold environments. Stable and tunable electrothermal performance is also achieved under ambient conditions (Fig. S15–S17). Repeated on–off cycling tests further confirm the stable electrothermal response and operational durability of WPPCF under practical switching operation (Fig. S18). Overall, the tunable, and stable Joule-heating performance of WPPCF demonstrates its potential as a flexible

electrothermal textile for reliable personal thermal management.

4 Conclusions

In this work, a multifunctional WPU/PBFD0/PDA/CF conductive textile was fabricated through a fully solution-based process. The rationally designed interfacial modification and encapsulation engineering endow the optimized WPPCF with a high electrical conductivity of 454.5 S m⁻¹, as well as exceptional environmental stability, washing resistance, and mechanical bending durability. Owing to its well-established continuous conductive network, WPPCF achieves an efficient electromagnetic interference shielding, with SET reaching a maximum of 41.74 dB. Taking advantage of its tunable electromagnetic response, a sandwich-structured wireless passive strain sensor was assembled, which realizes quantitative dual-parameter strain detection via resonant frequency shift and reflected S_{11} amplitude variation. In addition, WPPCF exhibits rapid, tunable, and stable Joule-heating performance under low-temperature conditions, reaching a maximum temperature of 112.7 °C at 5 V in an environment of approximately -25 °C. This work provides a practical solution-processing strategy for high-performance multifunctional conductive textiles, offering a promising material platform for the integrated development of wearable electromagnetic protection, wireless sensing, and intelligent thermal management devices.

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Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Qiangqiang Wang: Conceptualization, investigation, data curation, writing–original draft, experimental design, Wenzhong Zou: Experimental design, validation. Hongwen Jin: Data curation, validation. Chuankai Ji: Investigation, experimental design. Gu Liu: Conceptualization, investigation, validation. Liuying Wang: Methodology, validation, supervision. Da Liu: Methodology, conceptualization. Jin Zhou: Methodology, investigation. Renbing Wu: Conceptualization, supervision, writing–review & editing,

Methodology, project administration, funding acquisition. All the authors have approved the final manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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Solution-processable n-type conducting polymer smart textiles for multifunctional wearable electronics

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The EMI shielding effectiveness can be calculated by Eq. (S1-S3),

$$SE_T(dB) = 10 \lg \left(\frac{1}{T} \right) \quad (S1)$$

$$SE_A(dB) = 10 \lg \left(\frac{1-R}{T} \right) \quad (S2)$$

$$SE_R(dB) = 10 \lg \left(\frac{1}{1-R} \right) \quad (S3)$$

where T, R and A are the transmission, reflection and absorption coefficients, respectively.

$$R = |S_{11}^2| \quad (S4)$$

$$T = |S_{21}^2| \quad (S5)$$

$$R = 1 - A - T \quad (S6)$$

where S₁₁ and S₂₁ are input reflection and forward transmission coefficients, respectively.

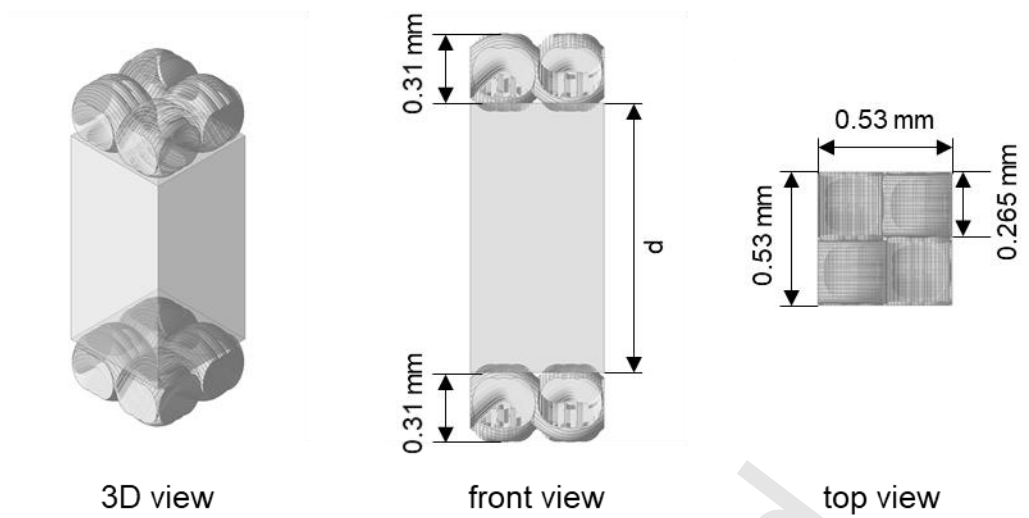


Figure S1. The geometric model and parameters of the WPPCF wireless strain sensor.

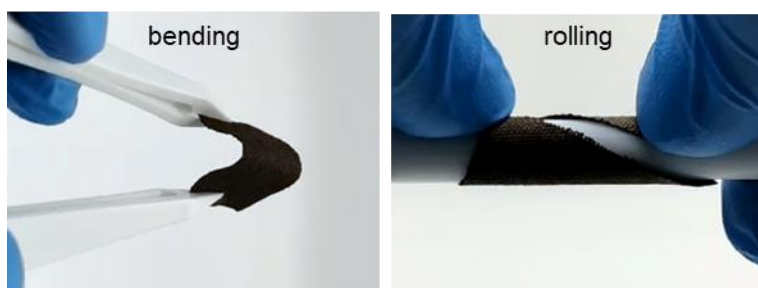


Figure S2. Photographs of the flexibility demonstrations of WPPCF, including bending and rolling deformation.

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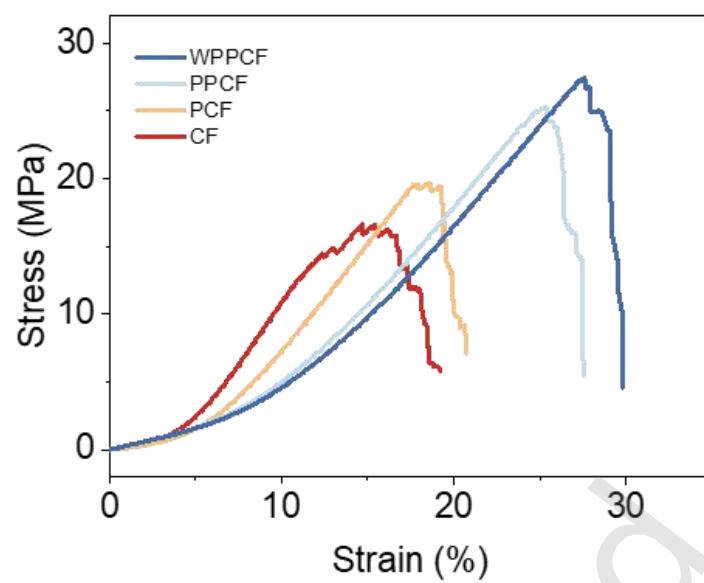


Figure S3. The stress-strain curves of CF, PCF, PPCF and WPPCF.

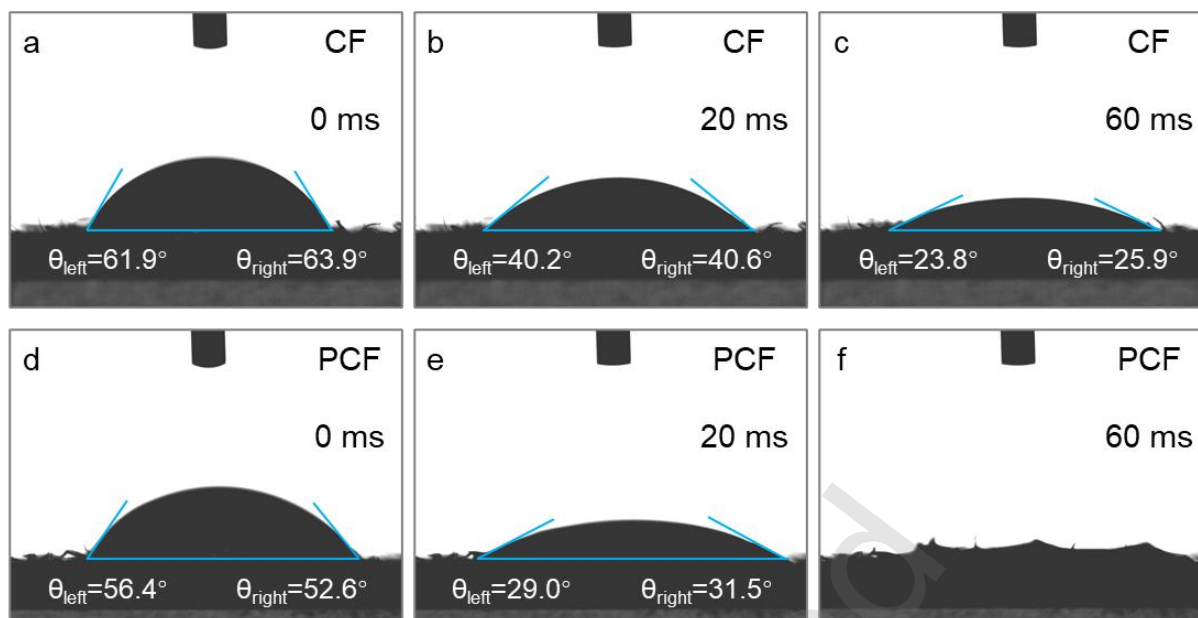


Figure S4. Time-dependent water contact-angle images of (a-c) CF and (d-f) PCF. PCF shows a lower initial contact angle and faster droplet spreading/absorption than CF, indicating improved surface wettability after PDA modification.

Water contact-angle measurements were first performed to compare the surface wettability of CF and PCF. As shown in Figure S4, CF exhibits an initial contact angle of approximately 62.9°, which gradually decreases to about 24.9° after 60 ms. In contrast, PCF shows a lower initial contact angle of approximately 54.5° and undergoes faster droplet spreading/absorption, with the water droplet almost completely disappearing within 60 ms. This result indicates that PDA modification improves the surface wettability of cotton fabric, which is favorable for the subsequent infiltration and spreading of the PBFDO/DMAc dispersion during dip-coating.

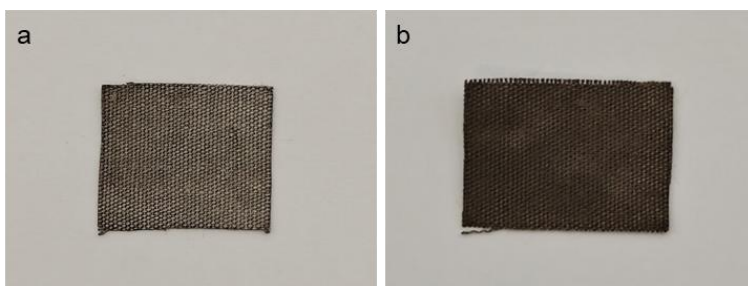


Figure S5. Photographs of (a) PDA-free CF and (b) PDA-modified PCF after one PBFDO dip-coating cycle.

The role of PDA in the initial PBFDO deposition was further examined by comparing the visual appearance of the fabrics after only one PBFDO dip-coating cycle. As shown in Figure S5, the PDA-free control fabric exhibits a lighter and less uniform color after dip-coating, suggesting insufficient and uneven PBFDO deposition. By contrast, the PDA-modified fabric becomes darker and more homogeneous under the same treatment. This visual difference supports that the PDA interfacial layer facilitates more uniform PBFDO deposition on the cotton fibers.

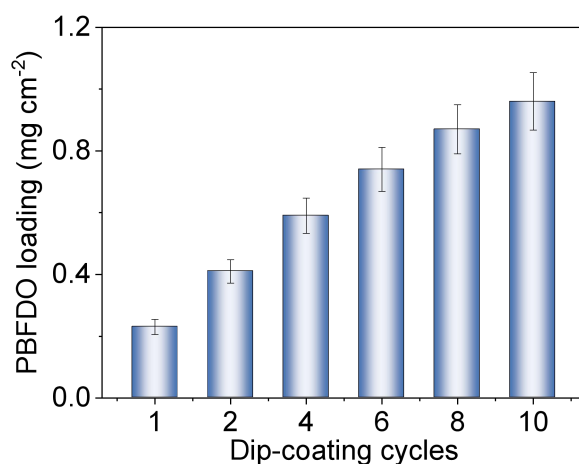


Figure S6. PBFD0 loading of PDA-free control fabrics as a function of dip-coating cycles.

The PBFD0 loading of PDA-free control fabrics was also recorded during repeated dip-coating. As shown in Figure S6, the loading increases gradually with increasing dip-coating cycles, confirming the progressive accumulation of PBFD0 on the textile. However, compared with the PDA-modified fabric discussed in the main text, the PDA-free control shows lower PBFD0 uptake under the same dip-coating conditions. This comparison further demonstrates that PDA modification provides a more favorable interfacial layer for PBFD0 deposition.

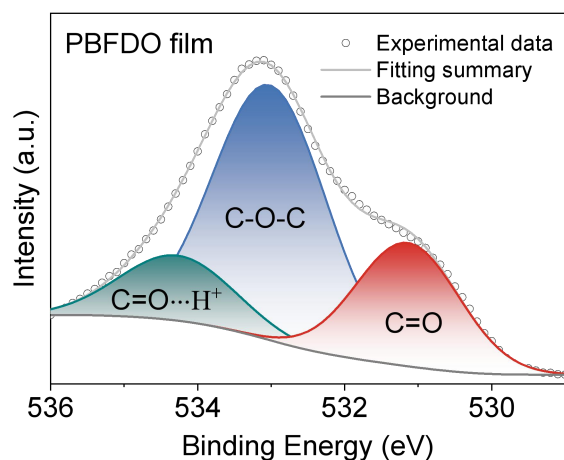


Figure S7. High-resolution O 1s XPS spectrum of the neat PBFDO film. The O 1s spectrum was fitted with three components assigned to proton-associated carbonyl oxygen ($\text{C}=\text{O}\cdots\text{H}^+$), furan-ring/C-O-C oxygen, and non-protonated carbonyl oxygen ($\text{C}=\text{O}$).

High-resolution O 1s XPS analysis was performed on a neat PBFDO film to evaluate the proton-compensated state of PBFDO. As shown in Figure S7, the O 1s spectrum was fitted with three components corresponding to proton-associated carbonyl oxygen ($\text{C}=\text{O}\cdots\text{H}^+$), furan-ring/C-O-C oxygen, and non-protonated carbonyl oxygen ($\text{C}=\text{O}$). Based on the carbonyl-related peak areas and considering two carbonyl groups in each PBFDO repeat unit, the proton-compensated doping ratio was estimated to be 74.1% per repeat unit. This result supports the stable n-doped state of the PBFDO used in this work.

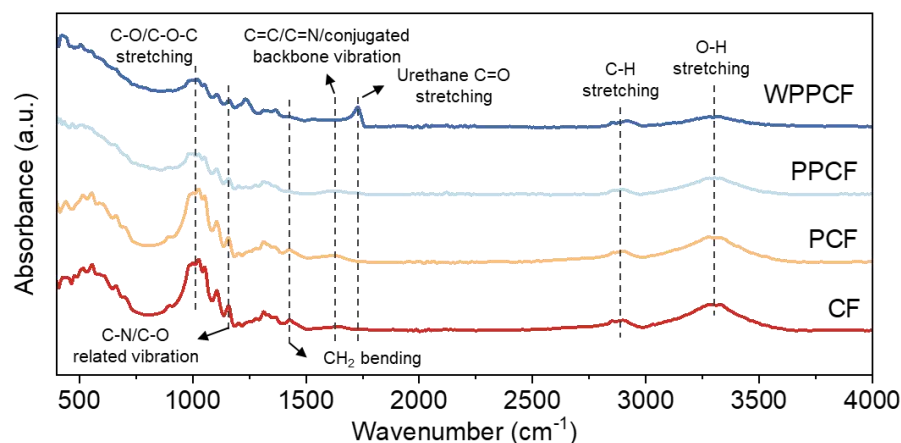


Figure S8. FTIR spectra of CF, PCF, PPCF, and WPPCF, showing the chemical evolution of the fabrics during PDA modification, PBFDO deposition, and WPU encapsulation.

As shown in Figure S8, CF exhibits the typical absorption bands of cellulose, including the broad O–H stretching band at around 3300 cm^{-1} , C–H stretching near 2900 cm^{-1} , and C–O/C–O–C vibrations in the fingerprint region. After PDA modification, PCF retains the main cellulose features, while slight changes in the $1500\text{--}1650\text{ cm}^{-1}$ region can be associated with the aromatic and C=N/C=C-related structures of the thin PDA layer. After PBFDO deposition, the cellulose-related bands become less pronounced, accompanied by the appearance of absorptions related to carbonyl groups and the conjugated PBFDO backbone. This result indicates that PBFDO was successfully deposited on the fiber surface and partially covered the underlying cellulose signal. For WPPCF, the more distinct carbonyl absorption in the $1700\text{--}1730\text{ cm}^{-1}$ region, together with the strengthened absorption near $1230\text{--}1250\text{ cm}^{-1}$, supports the introduction of the WPU encapsulation layer. These FTIR results further confirm the sequential construction of WPPCF through PDA interfacial modification, PBFDO coating, and WPU protection.

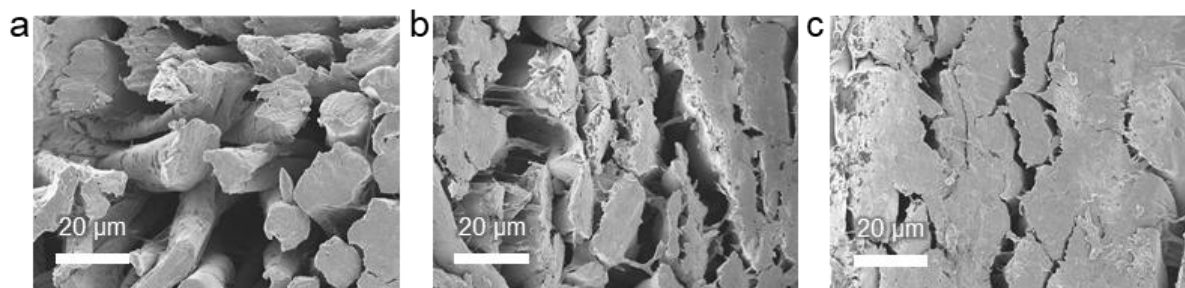


Figure S9. The SEM images from a cross-sectional perspective of (a) WPPCF-1, (b) WPPCF-4, (c) WPPCF-10.

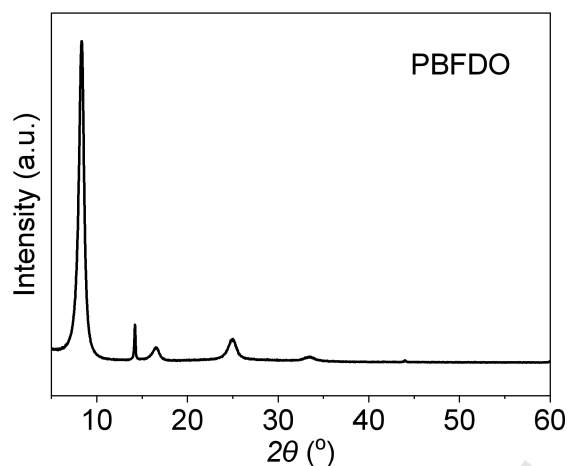


Figure S10. XRD pattern of the neat PBFDO film sample, showing the intrinsic partially ordered packing structure of PBFDO.

The intrinsic crystallinity of PBFDO was further examined using a neat PBFDO reference sample. As shown in Figure S10, neat PBFDO exhibits a strong low-angle diffraction peak at approximately 8.3° , together with additional diffraction features at around 14.2° , 16.5° , and 24.9° . The low-angle diffraction peak corresponds to a relatively large periodic spacing of approximately $10.6 \text{ \AA}$, indicating ordered packing of the PBFDO chains. The high-angle diffraction feature at approximately 24.9° gives a d-spacing of about $3.57 \text{ \AA}$, which can be associated with π - π stacking between conjugated polymer backbones. These diffraction features suggest that neat PBFDO possesses a partially ordered molecular-packing structure rather than being completely amorphous.

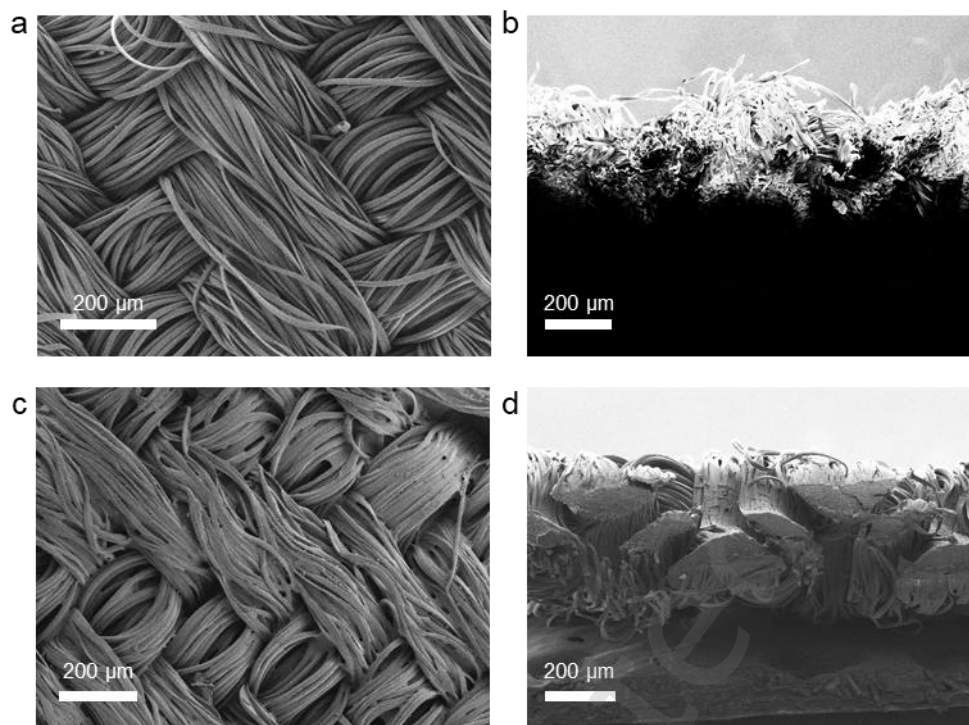


Figure S11. SEM images of twill nylon fabric before and after PBFDO impregnation. (a,b) Top-view and cross-sectional SEM images of the pristine twill nylon fabric. (c,d) Top-view and cross-sectional SEM images of the PBFDO-impregnated twill nylon fabric.

To further evaluate the generalizability of the solution-based PBFDO impregnation strategy, twill nylon fabric was selected as another textile substrate. SEM observations show that the pristine twill nylon fabric exhibits a clear woven texture and fibrous morphology in both top-view and cross-sectional images (Figure S13a, b). After PBFDO impregnation, the overall woven structure is still retained, while PBFDO is deposited within the inter-fiber voids. This feature is more clearly observed from the cross-sectional SEM image, where the gaps between fiber bundles are partially filled by PBFDO (Figure S13c, d).

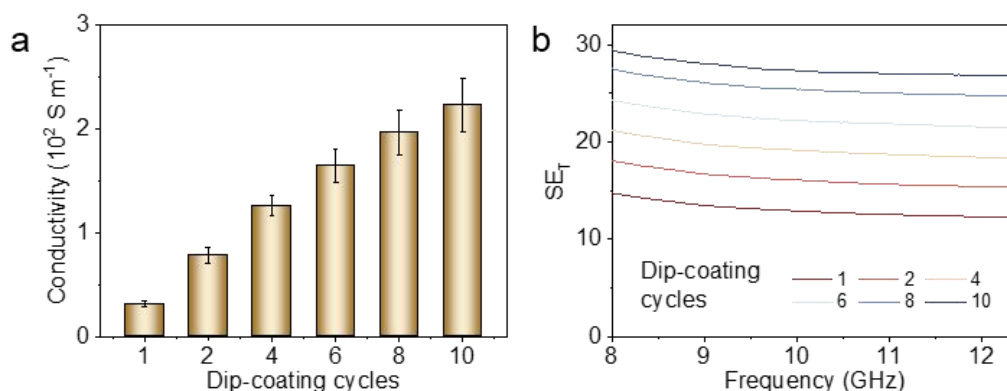


Figure S12. (a) Electrical conductivity of PBFDO-impregnated twill nylon fabrics with different dip-coating cycles. (b) X-band EMI shielding performance of PBFDO-impregnated twill nylon fabrics with different dip-coating cycles.

The electrical conductivity of the PBFDO-impregnated twill nylon fabric increases progressively with the number of dip-coating cycles (Figure S14). The conductivity rises from $31.12 \pm 2.86 \text{ S m}^{-1}$ after one cycle to $223.51 \pm 25.68 \text{ S m}^{-1}$ after ten cycles, confirming the gradual formation of conductive pathways in the nylon textile. This value is lower than that of WPPCF prepared from cotton fabric, which is probably related to the weaker swelling and lower PBFDO uptake/retention of the twill nylon fibers during solution impregnation. The EMI shielding performance also follows the same trend. As shown in Figure S15, the maximum SE_T values of the PBFDO-impregnated twill nylon fabrics increase from 14.77 to 29.49 dB as the dip-coating cycles increase from 1 to 10. These results demonstrate that the present PBFDO solution-impregnation strategy can be extended beyond cotton fabric and is applicable to other textile substrates, although the final conductivity and shielding performance depend on the substrate structure and its affinity toward PBFDO deposition.

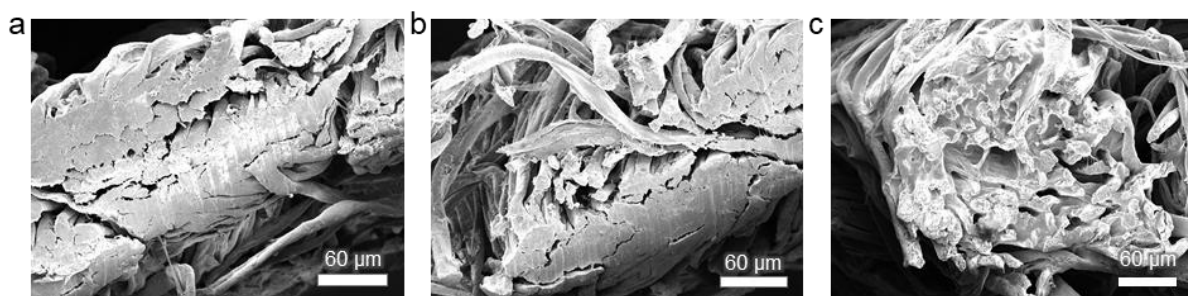


Figure S13. The SEM images from a cross-sectional perspective of (a) initial WPPCF, (b) WPPCF after 20 washing cycles, (c) PPCF after 20 washing cycles.

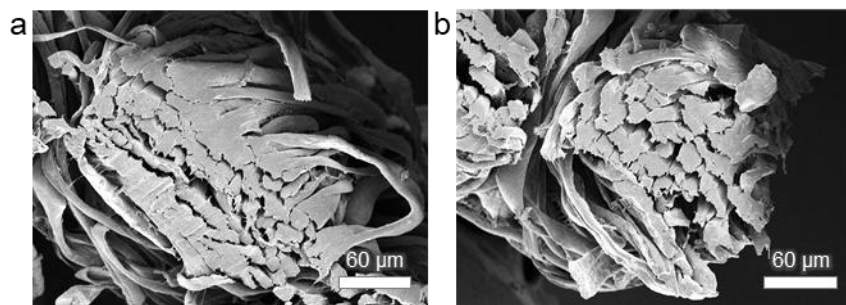


Figure S14. The SEM images from a cross-sectional perspective of (a) initial WPPCF, (b) WPPCF after 1000 bending cycles.

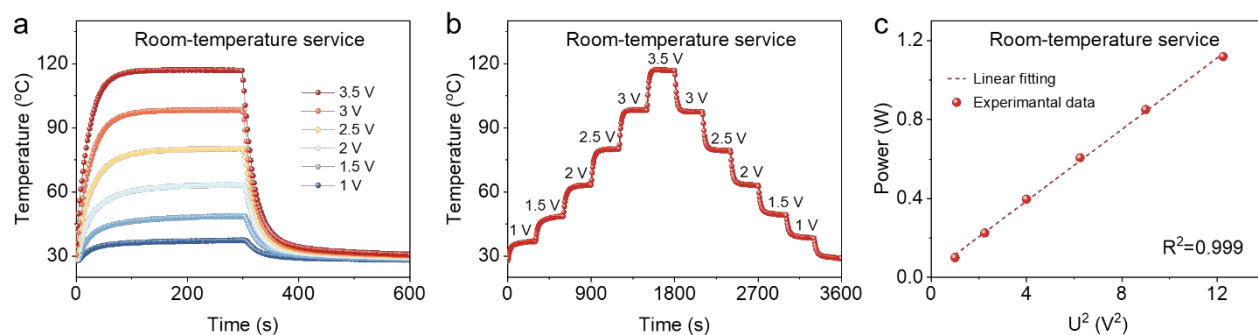


Figure S15. Electric heating performance of WPPCF in service at room temperature. (a) Temperature-time profiles at different voltages. (b) Stepwise heating and cooling response under cyclic voltage switching between 1 and 5 V. (c) Linear relationship between electrical power and U^2 .

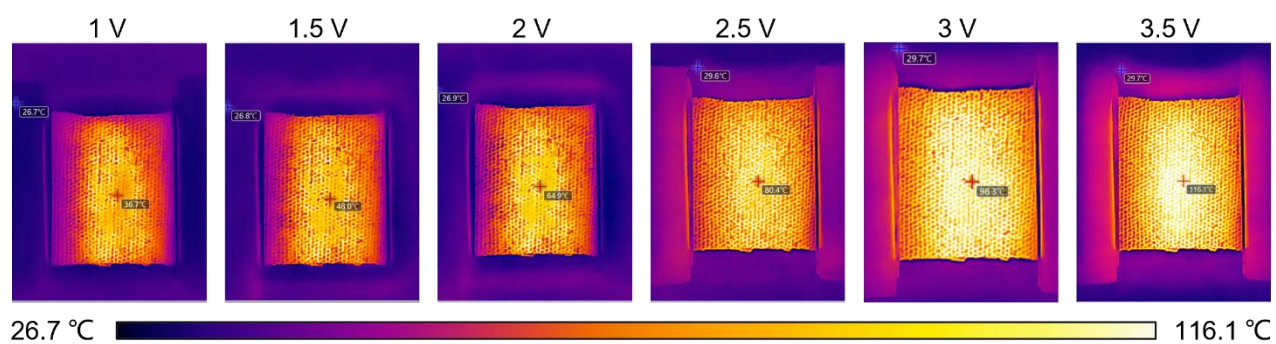


Figure S16. Infrared thermal images under applied voltages from 1 to 3.5 V of WPPCF in service at room temperature.

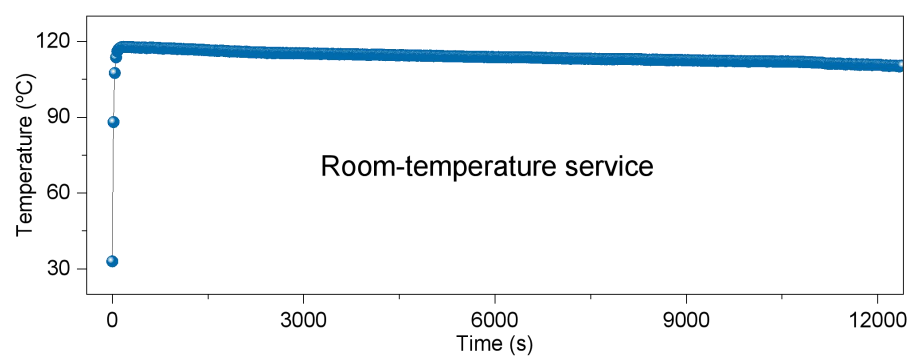


Figure S17. Long-term Joule-heating stability at room temperature.

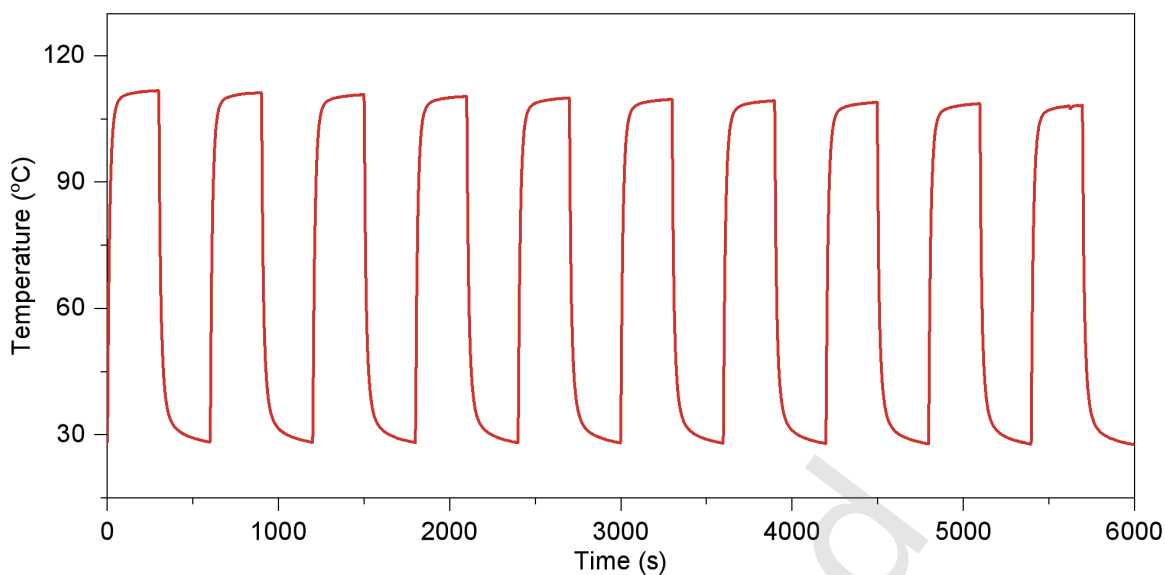


Figure S18. On-off Joule-heating cycling stability of WPPCF under repeated voltage switching.

To further evaluate the electrothermal durability of WPPCF under repeated switching operation, on-off Joule-heating cycling tests were performed. As shown in Figure Sx, the sample was powered for 300 s and then turned off for 300 s in each cycle, and the test was repeated for 10 cycles. WPPCF shows rapid heating after each power-on step and fast cooling after power removal. The maximum temperature remained at 109.87 ± 1.14 °C during the 10 cycles, with only a slight decrease from 111.72 °C in the first cycle to 108.23 °C in the tenth cycle. The corresponding peak-temperature retention was 96.9%. These highly repeatable heating/cooling profiles demonstrate the stable electrothermal response and good operational durability of WPPCF under repeated on-off switching.

Table S1. Conductivity of WPPCF with different PBFDO dip-coating cycles.

Dip-coating cycles	$\sigma 1$ (S m ⁻¹)	$\sigma 2$ (S m ⁻¹)	$\sigma 3$ (S m ⁻¹)	$\sigma 4$ (S m ⁻¹)	$\sigma 5$ (S m ⁻¹)	Average (S m ⁻¹)	standard deviation
1	44.50	49.17	50.33	43.31	46.54	46.77	2.98
2	117.98	108.54	106.14	120.32	112.66	113.13	6.03
4	233.82	219.02	237.50	215.24	225.47	226.21	9.46
6	333.25	339.27	309.03	302.85	319.60	320.80	15.48
8	437.31	403.31	445.75	394.64	418.14	419.83	21.72
10	479.20	452.12	491.13	418.92	431.17	454.51	30.69

Table S2. Conductivity of WPPCF with different air exposure time.

Air exposure time (days)	σ_1 (S m⁻¹)	σ_2 (S m⁻¹)	σ_3 (S m⁻¹)	σ_4 (S m⁻¹)	σ_5 (S m⁻¹)	Average (S m⁻¹)	standard deviation
1	429.58	491.14	486.12	434.27	470.73	462.37	28.84
5	486.42	481.84	430.24	434.51	467.79	460.16	26.32
10	487.83	424.93	429.71	482.70	466.98	458.43	29.47
20	475.42	428.07	471.56	459.72	431.68	453.29	22.18
30	471.50	421.89	467.45	425.66	455.05	448.31	23.24

Table S3. Conductivity of WPPCF with different washing cycles.

Washing cycles	σ_1 (S m ⁻¹)	σ_2 (S m ⁻¹)	σ_3 (S m ⁻¹)	σ_4 (S m ⁻¹)	σ_5 (S m ⁻¹)	Average (S m ⁻¹)	standard deviation
1	463.06	449.91	414.19	418.41	440.73	437.26	20.77
3	459.19	408.77	445.62	436.15	413.12	432.57	21.43
5	459.05	403.42	408.22	444.08	433.63	429.68	23.64
10	458.79	443.01	400.15	405.21	432.00	427.83	24.92
20	393.82	461.47	443.27	399.66	430.57	425.76	28.75

Table S4. Conductivity of PPCF with different washing cycles.

Washing cycles	$\sigma 1$ (S m ⁻¹)	$\sigma 2$ (S m ⁻¹)	$\sigma 3$ (S m ⁻¹)	$\sigma 4$ (S m ⁻¹)	$\sigma 5$ (S m ⁻¹)	Average (S m ⁻¹)	standard deviation
0	447.86	520.41	507.75	440.95	464.37	476.27	35.83
1	433.91	426.18	389.65	385.43	399.72	406.98	21.86
3	407.67	351.12	345.73	397.80	363.98	373.26	27.93
5	348.19	290.57	338.13	303.68	285.08	313.13	28.46
10	195.38	243.67	235.24	190.78	206.37	214.29	23.85
20	213.96	170.69	206.40	180.53	166.57	187.63	21.37

Table S5. Conductivity of WPPCF with different bending cycles.

Bending cycles	σ_1 (S m⁻¹)	σ_2 (S m⁻¹)	σ_3 (S m⁻¹)	σ_4 (S m⁻¹)	σ_5 (S m⁻¹)	Average (S m⁻¹)	standard deviation
5	396.81	477.12	461.55	410.34	418.53	432.87	34.62
10	461.02	391.94	403.58	447.63	410.62	422.96	29.78
100	434.31	422.75	374.71	384.75	390.83	401.47	25.69
500	419.41	374.97	410.79	382.45	386.98	394.92	19.16
1000	362.36	412.19	402.53	370.75	375.83	384.73	21.48

Table S6. Geometric and electromagnetic parameters used in the HFSS simulation.

Parameter	Value/setting
Unit-cell size	0.53 mm × 0.53 mm
Yarn pitch	0.265 mm
Nominal yarn width	0.25 mm
Inter-yarn gap	0.015 mm
Yarn crimp amplitude	0.08 mm
Equivalent single-fabric thickness	0.31 mm
Silicone-rubber layer thickness	(d+0.070) mm before Boolean subtraction

The detailed geometric and electromagnetic parameters of the HFSS model are summarized in Table S7. The sensor was modeled as a periodic single-cell structure consisting of an upper low-conductivity WPPCF-1 layer, a silicone-rubber spacer, and a lower high-conductivity WPPCF-10 layer. Each conductive textile layer was represented by an equivalent plain-woven geometry containing two warp yarns and two weft yarns within a 0.53 mm × 0.53 mm unit cell. The yarns were modeled as curved polylines with circular cross-sections, an equivalent diameter of 0.15 mm, and a crimp amplitude of 0.08 mm, giving an equivalent single-fabric thickness of 0.31 mm. The spacer thickness d was defined as the distance between the inner surfaces of the upper and lower textile layers. To ensure conformal contact with the corrugated textile surfaces, the silicone-rubber spacer was constructed with a 0.035 mm overlap at each textile/rubber interface and Boolean-subtracted by the yarn geometries. The in-plane directions were assigned Primary–Secondary periodic boundaries, while Floquet ports were applied to the upper and lower boundaries to simulate normally incident electromagnetic waves.

Table S7. Conductivity of neat PBFDO film.

$\sigma 1$ (S cm ⁻¹)	$\sigma 2$ (S cm ⁻¹)	$\sigma 3$ (S cm ⁻¹)	$\sigma 4$ (S cm ⁻¹)	$\sigma 5$ (S cm ⁻¹)	Average (S cm ⁻¹)	standard deviation
1669.45	1618.12	1841.62	1890.36	1748.25	1754	114

The electrical conductivity of neat PBFDO was further measured using a four-point probe method. A neat PBFDO film was prepared from the same PBFDO/DMAc dispersion. The average film thickness was approximately 10 μm . Based on five measurements, the neat PBFDO film showed an electrical conductivity of 1754 ± 114 S cm⁻¹, confirming the high intrinsic charge-transport capability of PBFDO.