

Multifunctional folding-endurance poly(p-phenylene benzobisoxazole) nanofibers composite films for remarkable electromagnetic interference shielding and thermal management

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Nano Res., **Just Accepted Manuscript** • <https://doi.org/10.26599/NR.2026.94909084>

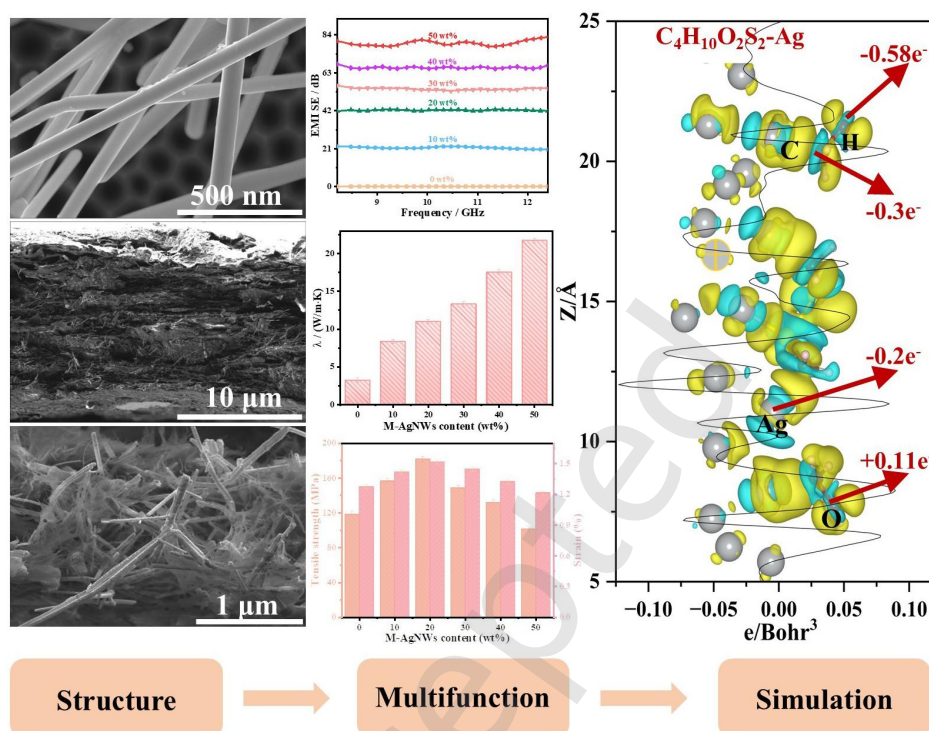
<https://www.sciopen.com/journal/1998-0124> on Aug. 4, 2026

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M-AgNWs/PNF composite films, fabricated via vacuum filtration and hot-pressing, deliver high σ of 4545 S/cm, X-band EMI SE of 81 dB, λ of 21.7 W/(m·K), and tensile strength of 181.1 MPa. DFT calculations reveal that HEDS adsorbs onto AgNWs through Ag-S coordination, driving M-AgNWs to form efficient conductive and dissipative networks within PNF, which significantly boosts the EMI shielding and mechanical properties.

Research Article

Multifunctional folding-endurance poly(p-phenylene benzobisoxazole) nanofibers composite films for remarkable electromagnetic interference shielding and thermal management

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Received: 11 July 2026; **Revised:** 31 July 2026; **Accepted:** 4 August 2026

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Cite this article: *Nano Research*, 2026, 19, 94909084 <https://doi.org/10.26599/NR.2026.94909084>

ABSTRACT: Pliant and versatile polymeric films engineered for electromagnetic interference (EMI) shielding play a pivotal role in driving the evolution of telecommunications, wearable electronics, and next-generation AI platforms. In this work, poly(p-phenylene benzobisthiazole) (PBO) fibers are subjected to sequential acid treatment with MSA/TFA mixture and subsequent deprotonation to afford well-defined PBO nanofibers (PNF). Water-dispersible silver nanowire (M-AgNWs) is synthesized via a controlled polyol reduction process coupled with Ag-S coordination surface functionalization. Then, M-AgNWs/PNF composite films are fabricated through vacuum-assisted filtration followed by thermal compression. The synthesized M-AgNWs/PNF composite films demonstrate remarkable multifunctional performance at a 50 wt% M-AgNWs loading, which deliver an electrical conductivity (σ) of 4545 S/cm, superior X-band EMI shielding (81 dB), a thermal conductivity (λ) of 21.7 W/(m·K), and the tensile strength can be flexibly tuned within the range of 101.3 MPa to 181.1 MPa. First-principles (DFT) simulation results confirm that HEDS adsorbs onto AgNWs through Ag-S coordination, and the functionalized M-AgNWs can form efficient electrically and thermally conductive networks within PNF, thereby improving the EMI shielding and mechanical properties of the M-AgNWs/PNF composite films. Furthermore, M-AgNWs/PNF composite films demonstrate rapid, reversible photothermal and electrothermal responses. Under simulated sunlight irradiation with a power density of 120 mW/cm², the surface temperature of M-AgNWs/PNF composite films rapidly rise from room temperature to 74.8°C. Concurrently, under a voltage of 3.5 V, the surface temperature quickly escalates to 79.4°C. This work offers an effective approach to fabricating lightweight, high-performance EMI shielding composites suitable for aerospace and integrated electronic devices.

KEYWORDS: electromagnetic interference shielding, poly(p-phenylene benzobisthiazole) nanofibers (PNF), silver nanowire (AgNWs), thermal management

1 Introduction

The continuous drive toward high frequencies, miniaturization, and high-power integration in flexible electronics have drastically escalated the challenges associated with electromagnetic pollution [1-3]. The resulting electromagnetic radiation and heat accumulation increasingly jeopardize both human health and device reliability, urgently demanding the development of next-generation multifunctional, high-performance electromagnetic interference (EMI) shielding materials [4, 5].

Achieving the synergistic integration of ultra-thinness, high toughness, superior thermal conductivity, and exceptional EMI shielding effectiveness (SE) remain a formidable challenge for flexible films [6-8]. Although traditional metal-based shielding materials offer high EMI SE [9, 10], which are inherently limited by susceptibility to corrosion, high density, and poor mechanical flexibility [11, 12]. Conversely, polymer-based composites, characterized by low density, facile processability, and corrosion resistance, have emerged as promising alternatives [13, 14]. By incorporating advanced conductive nanofillers, such as carbon nanotubes (CNTs) [15, 16], MXenes [17, 18], and graphene [19, 20] into the polymer matrix to construct a continuous conductive network, the EMI shielding efficiency, thermal conductivity, and mechanical properties of the resulting films can be simultaneously enhanced [21-23]. Through solution casting and hot impregnation, Yang et al. [24] fabricated polyimide (PI)/CNT composite films. When a mass ratio of PI to CNT was 6:4, PI/CNT composite films exhibited a tensile strength of 67.2 MPa coupled with a 39 dB EMI SE. Meanwhile, Wang et al. [25] prepared polyetherimide-functionalized $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets (f- $\text{Ti}_3\text{C}_2\text{T}_x$)/polybenzoxazole nanofiber (PNF) composite films using a sol-gel method. At a filler content of 70 wt%, the f- $\text{Ti}_3\text{C}_2\text{T}_x$ /PNF film demonstrated an EMI SE of 35 dB, a high tensile strength of 125.1 MPa, and a thermal conductivity coefficient (λ) of 5.82 W/(m·K). However, the deficient interfacial bonding between the filler and matrix phases primarily compromises the EMI SE and mechanical robustness of these fabricated films [26-28]. Consequently, it fails to meet the rigorous application requirements dictated by high-radiation environments, such as aerospace systems, military defense equipment, and high-precision sensitive instruments [29, 30].

Owing to their outstanding electrical, thermal, and mechanical properties, silver nanowires (AgNWs) represent highly promising conductive fillers for advanced flexible EMI shielding [31-33]. Utilizing vacuum filtration, Nguyen et al. [34] prepared alternating multilayer boron arsenide (BA)/aramid nanofibers (ANF)/AgNWs (AMS) composite films. When the AMS was composed of three layers of ANF containing 50 wt% BA and two layers of AgNWs stacked alternately, it exhibited a tensile strength of 137.83 MPa

accompanied by a 54 dB EMI SE at a thickness of 30 mm. Utilizing vacuum-assisted filtration, Li et al. [35] developed flexible PI/MXene/AgNWs (PMA) composite films. The resulting the PMA achieved a 67 dB EMI SE given a 2:1 MXene/AgNWs mass ratio, but suffered a reduced tensile strength of 5.7 MPa. This deficiency stems from the high surface energy of AgNWs, which causes poor interfacial compatibility with the matrix. Moreover, high filler loadings inevitably trigger AgNWs agglomeration, thereby hindering effective thermal management and mechanical reinforcement [36-38]. In previous work [39], 4-aminobenzothiol (4-ATP) was used to modify the surface of AgNWs with amino groups, then they were combined with PNF acid solution. AgNWs-NH₂/PNF composite films were synthesized utilizing a sol-gel method. Upon introducing 50 wt% AgNWs-NH₂, the AgNWs-NH₂/PNF exhibited a remarkable tensile strength of 202.4 MPa, accompanied by an outstanding λ value of 21.08 W/(m·K). Despite these promising metrics, the highly corrosive and toxic nature of TFA attacks the covalent and hydrogen bonds within the AgNWs and at the filler-matrix interface, which drastically suppresses the electrical conductivity and thwarts its potential for high-efficiency EMI shielding [40-42].

Poly(p-phenylene benzobisoxazole) (PBO) fibers are hailed as the “super fiber of the 21st century” due to their exceptional mechanical and thermal properties [43, 44]. In this work, PBO fibers are subjected to MSA/TFA mixed acid exfoliation and deprotonation treatment to obtain PNF. AgNWs is synthesized via a polyol method and subsequently modified with 2-hydroxyethyl disulfide (HEDS) to yield M-AgNWs. By integrating M-AgNWs with PNF, flexible multifunctional M-AgNWs/PNF composite films are successfully fabricated through a combination of vacuum-assisted filtration and hot-pressing processes. HEDS molecules are chemically adsorbed onto the surface of AgNWs via Ag-S coordination chemistry, while their terminal -OH groups form a dense hydrogen-bonding network with PNF, thereby constructing an efficient “chemical bridging” interface. This strategy overcomes the technical limitations of conventional AgNWs in polymer matrices, including facile aggregation due to high surface energy and poor interfacial compatibility, and achieves synergistic optimization of electromagnetic shielding performance and mechanical properties in M-AgNWs/PNF composite films. Accordingly, this work provides a new pathway for the development of high-performance flexible EMI shielding composites. The mutual interleaving of high-aspect-ratio M-AgNWs and PNF establishes a highly efficient conductive network that accelerated electron and phonon transport. Benefiting from this, M-AgNWs/PNF composite films deliver superior EMI SE, electrical/thermal conductivity, photothermal conversion, and Joule heating properties. This work establishes a pioneering paradigm to engineer adaptive, multifunctional polymer-based composite films, charting a new

path for applications in electronics integration and aerospace fields.

2 Experimental sections

2.1 Materials

Chemical reagents including silver nitrate (AgNO_3 , 99.8%), polyvinylpyrrolidone (PVP, $M_w \approx 5800$), and trifluoroacetic acid (TFA, 95%) were obtained from Tianjin Tiangan Chemical Technology Development Co., Ltd. and Shandong Keyuan Biochemical Co., Ltd., respectively, with the latter also providing poly(p-phenylene benzobisthiazole) fiber (PBO fiber). Ethylene glycol (EG, 99%) was sourced from Tianjin Fuyu Fine Chemical Co., Ltd. Shanghai Macklin Inc. supplied Ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, 99%), methanesulfonic acid (MSA, 99%), and 2-hydroxyethyl disulfide (98%, HEDS).

2.2 Synthesis of M-AgNWs

Typically, a homogeneous mixture was prepared by dissolving PVP (4.26 g) in 300 mL of EG, into which 4.14 mg of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was subsequently added under uninterrupted stirring. Next, a 50 mL aliquot was taken and dripped into an equal volume of EG solution that contained 0.68 g of AgNO_3 . Thermal treatment was carried out in an oven at 160°C for a duration of 180 min. To purify the product, three cycles of alternating centrifugation at 6000 and 4000 rpm (5 min per cycle) were performed using acetone and anhydrous ethanol. Ultimately, the harvested AgNWs were suspended in anhydrous ethanol for preservation.

The obtained AgNWs were dispersed in ethanol to form a 2 mg/mL dispersion. Meanwhile, 2-hydroxyethyl disulfide (HEDS) was added into the dispersion at an AgNWs to HEDS mass ratio of 5:1. After being agitated at 30°C for 12 h, the solution was allowed to age for an additional 12 h. The target M-AgNWs was recovered from the mixture through a two-step centrifugation process (3500 rpm, 5 min each).

2.3 Fabrication of M-AgNWs/PNF composite films

Initially, a yellow PBO acid solution was obtained by stirring PBO fibers in a co-solvent mixture of MSA/TFA (1:1, v/v) under continuous stirring at ambient temperature for 24 h. To fabricate PBO nanofibers (PNF), the as-prepared solution was introduced dropwise into deionized water under a high-speed fluid shear force of 15,000 rpm, followed by repeated washing with copious amounts of deionized water until a neutral pH was achieved. Afterward, 24 mg of M-AgNWs was introduced into 12 g of 1 wt% PNF dispersion. After 30 min of magnetic stirring and subsequent vacuum filtration, the blend was consolidated via hot-pressing at 90°C for 24 h to yield M-AgNWs/PNF composite films.

2.4 Characterization

A Shimadzu-7000 diffractometer (Shimadzu, Japan) was utilized to acquire X-ray diffraction (XRD) data ($\lambda=0.154$ nm). A Hitachi SU8010 field emission scanning electron microscope (Hitachi Corp., Japan) was employed to capture Scanning electron microscope (SEM) images of the samples under an acceleration voltage of 5 kV. To determine the electrical conductivity of the samples, an RTS-8 instrument (Guangzhou Four Probes Technology Co., China) was applied. For EMI shielding evaluation, a Vector Network Analyzer (MS4644A, Anritsu Co., Japan) was configured to operate under the waveguide modality within the X-band. The measurements followed the ASTM D5568-08 specification, requiring a precise sample geometry of 22.86 mm $\times$ 10.16 mm $\times$ 6.00 mm. In compliance with ISO 1184-1983, a microcomputer-controlled electronic universal testing machine (Instron Bluehill LE, Instron Co., USA) was utilized to measure the mechanical performance at a velocity of 20 mm/min. A CELHXUV 300 xenon lamp served as the light source to drive the photothermal conversion process. For subsequent thermal mapping, a high-resolution infrared thermographic camera (HM-TPH36-10VF/W, Hikmicrotech Co., China) was employed. A fixed gap of 30 cm was set between the sample and the infrared thermal imager during temperature monitoring. Thermal conductivity data were acquired on a Hot Disk TPS2200 instrument (AB Corp., Sweden) according to the specifications of ISO 22007-2:2008. The electrothermal response was recorded by integrating the samples into a circuit powered by an eTM1520 DC power supply (eTOMMENS Co., China).

3 Results and discussion

3.1 Structural topography and analysis of M-AgNWs/PNF composite films

The preparation pathway of M-AgNWs/PNF composite films is schematically depicted in Fig. 1(a). Firstly, the surface of AgNWs is chemically tailored with HEDS to obtain M-AgNWs. In parallel, PBO is dissolved in a mixed-acid medium for protonation, which is then converted into a well-dispersed PNF solution through a subsequent deprotonation treatment. Finally, vacuum-assisted filtration and a subsequent hot-pressing process are implemented to achieve M-AgNWs/PNF composite films. The surface wettability of PNF films and M-AgNWs/PNF composite films is illustrated by the contact angle values in Fig. S1. PNF films exhibit a contact angle of 74.98°, demonstrating its hydrophilic nature. Although the insertion of M-AgNWs elevates the contact angle of M-AgNWs/PNF composite films to 84.98°, M-AgNWs/PNF composite films still exhibit a characteristic hydrophilic behavior. The hydrophilic nature originates from the numerous polar moieties (-OH) on the M-AgNWs surface. Due to their high affinity, these groups interact closely with water molecules via robust hydrogen bonds and intermolecular forces, which significantly enhances the water trapping capability of M-AgNWs/PNF composite films. The morphology of AgNWs is

examined via the SEM image in Fig. 1(b), which shows cases exceptional uniformity and a smooth surface profile. Meanwhile, Fig. 1(c) presents the cross-sectional SEM image of M-AgNWs/PNF composite films, which shows a dense and layered structure, and M-AgNWs is uniformly embedded in PNF and overlap with each other to form an efficient thermal and electrical conductivity network (Fig. 1(d)). Following HEDS modification of AgNWs, the -OH groups on the surface of M-AgNWs can form strong interfacial bonds through hydrogen bonding and electrostatic interactions, amongst other mechanisms. These bonds facilitate the uniform dispersion of M-AgNWs within PNF, thereby preventing stress concentration caused by agglomeration. When M-AgNWs are composited with PNF, the uniformly dispersed M-AgNWs intertwine with the PNF via interfacial bonding forces to form a continuous conductive and thermally conductive network. The dense and layered microstructure is conducive to strengthening M-AgNWs and PNF interfacial interactions, thereby promoting the electrical and mechanical performance of the composite films. Following water sonication and immersion in 1 M HCl and NaOH solutions for 1 h (Fig. S2), M-AgNWs/PNF composite films sustain their primitive structure, verifying their excellent chemical stability and corrosion resistance. Additionally, M-AgNWs/PNF composite films show superb flexibility and toughness (Fig. 1(e)). No cracking or fracturing occurred even when M-AgNWs/PNF composite films are configured into an origami airplane, coiled around on glass rod, or subjected to a 500 g weight, indicating great potential for flexible applications.

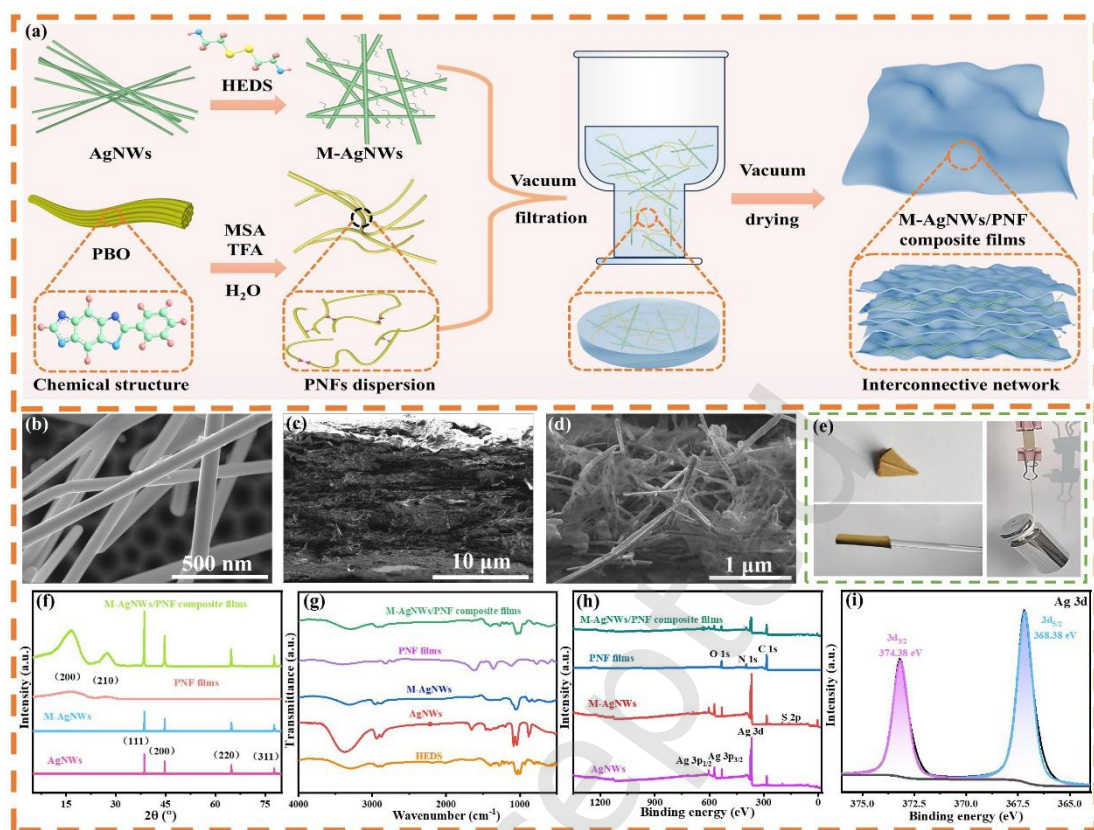


Figure 1 (a) Schematic diagram for the fabrication of M-AgNWs/PNF composite films. (b) SEM images of AgNWs and (c, d) cross-sectional SEM images of M-AgNWs/PNF composite films. (e) Digital photos of M-AgNWs/PNF composite films bearing a weight of 500 g and exhibiting excellent flexibility. (f) XRD patterns and (h) XPS spectra of AgNWs, M-AgNWs, PNF films and M-AgNWs/PNF composite films. (g) FT-IR spectra of HEDS, AgNWs, M-AgNWs, PNF films and M-AgNWs/PNF composite films. (i) High-resolution Ag 3d spectra of M-AgNWs/PNF composite films.

To resolve the crystalline structures, the XRD spectra across AgNWs, M-AgNWs, PNF films, and M-AgNWs/PNF composite films are delineated in Fig. 1(f). The AgNWs pattern locates at 38.4°, 44.8°, 64.8°, and 77.8° index perfectly to (111), (200), (220), and (311) crystal lattices, respectively. Those of M-AgNWs are identical to the pristine ones with no obvious peak shifts or new peaks, indicating that surface functionalization maintains the crystal structure of AgNWs. PNF films show two distinct reflections at 16.6° and 27.3°, matching the (200) and (210) planes. Upon forming M-AgNWs/PNF composite films, the diffraction features of both independent constituents are well preserved, which substantiates the successful integration of M-AgNWs within PNF.

The Fourier Transform Infrared (FT-IR) spectra trace the chemical structures of HEDS, AgNWs, M-AgNWs, PNF films, and M-AgNWs/PNF composite films (Fig. 1(g)). The stretching mode of surface

O-H groups and residual C=O bonds of PVP in pristine AgNWs appear at 3321 cm^{-1} and 1660 cm^{-1} , respectively. For M-AgNWs, the introduction of HEDS induces an apparent shift of the O-H stretching band toward a lower wavenumber (from 3321 to 3310 cm^{-1}). This phenomenon stems from the extensive -OH moieties of the modifier, which increase the local hydrogen bonding density upon surface adsorption onto AgNWs, thereby triggering the observed redshift. Simultaneously, the drastic attenuation of the 1660 cm^{-1} feature indicates a substantial removal of surface PVP, confirming that AgNWs were successfully functionalized. Regarding PNF, the oxazole ring presents its C=N stretching vibration at 1621 cm^{-1} , whereas the co-contributions of -OH and -NH₂ are evidenced by the broad peak at 3407 cm^{-1} . Because the MSA/TFA mixed acid successfully exfoliate PBO fibers, during which the oxazole rings are protonated and cleaved into -COOH and -NH₂ groups. The spectral overlap of these characteristic peaks in M-AgNWs/PNF composite films confirm their successful fabrication.

The XPS profiles depict the elemental states of AgNWs, M-AgNWs, PNF films, and M-AgNWs/PNF composite films (Fig. 1(h)). In the case of AgNWs, the characteristic signals of Ag 3d_{5/2}, Ag 3d_{3/2}, Ag 3p_{3/2}, and Ag 3p_{1/2} are clearly identified at 364.5 eV, 377.2 eV, 572.8 eV, and 602.2 eV, respectively. After HEDS modification, the spectra of M-AgNWs retain the relevant characteristic peaks of Ag while also showing a S 2p characteristic peak at 164.9 eV, indicating that the sulfur-containing molecules have been successfully grafted onto AgNWs via the formation of Ag-S coordination. PNF films show C 1s, N 1s, and O 1s peaks, corresponding to 283.6 eV, 402.3 eV, and 531.9 eV, respectively. A superposition of the distinctive peaks from both constituents is clearly observed in M-AgNWs/PNF composite films, which provides additional confirmation for the accomplished integration of the two phases. The metallic integrity of AgNWs is substantiated by the Ag 3d spectra (Fig. 1(i)), where the 3d_{5/2} and 3d_{3/2} reflections emerge at 368.38 and 374.38 eV without demonstrating any high binding energy displacement, rule out the possibility of surface oxidation. Additionally, the N 1s and C 1s core-level signals of M-AgNWs/PNF composite films are illustrated in Fig. S3. For the N 1s region, the signals at 398.5 and 400.3 eV match C-N and C-NH configurations. The fine C 1s spectrum exhibits five constituent peaks at 284.1 eV, 285.7 eV, 286.3 eV, 287.8 eV, and 288.9 eV, revealing the co-existence of C-C, C-N, C-O, N-C=O, and O-C=O environments. Specifically, the O-C=O bond originates from -COOH generated via the ring-opening cleavage of the oxazole ring.

3.2 EMI Shielding Performance of M-AgNWs/PNF composite films

The EMI shielding performance is closely governed by its electrical conductivity (σ). As depicted in Fig.

2(a), the incorporation of M-AgNWs leads to a substantial enhancement in the σ of M-AgNWs/PNF composite films, triggering a radical transformation from an electrical insulator to a conductor [45, 46] At 10 wt% M-AgNWs loading, M-AgNWs/PNF composite films deliver a low σ of 1.31 S/cm. This indicates that the isolated M-AgNWs is insufficient to span the percolation threshold, failing to construct a continuous transport highway across PNF. As the M-AgNWs content rises from 20 wt% to 50 wt%, the σ undergoes a dramatic surge from 104 S/cm to 4545 S/cm. When integrated into an electrical circuit, M-AgNWs/PNF composite films successfully illuminate an LED light (Fig. S4(a)). Owing to the formation of dense hydrogen networks between the hydroxyl-abundant M-AgNWs and PNF, a superb enhancement in electrical performance was achieved. These robust interfacial interactions facilitate the uniform dispersion of AgNWs and the construction of a highly interconnected electron transport network [47, 48].

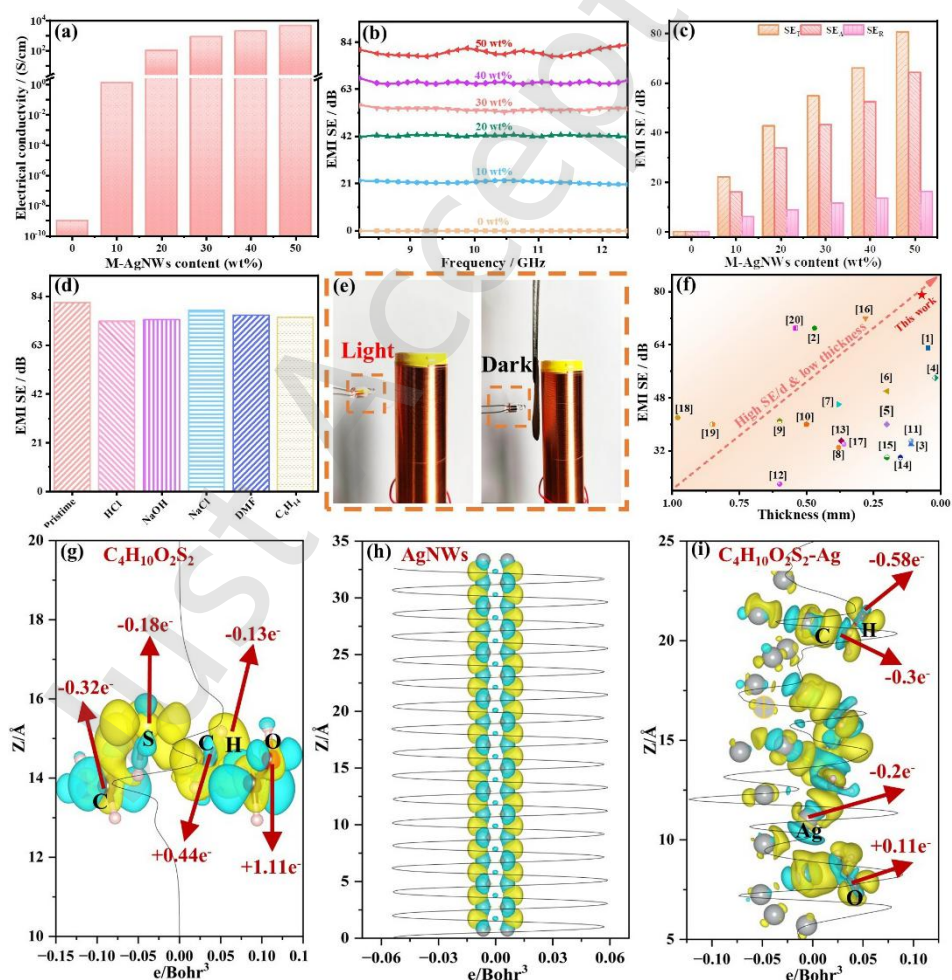


Figure 2 (a) σ , (b) EMI SE and (c) the corresponding SE_T, SE_A and SE_R of M-AgNWs/PNF composite films. (d) Comparison for EMI SE of M-AgNWs/PNF composite films after immersion in different liquids compare to the original sample. (e) EMI shielding evaluations of M-AgNWs/PNF composite films blocking Tesla coil radiation. (f) Comparison of EMI shielding performance between M-AgNWs/PNF composite

films and reported works. The views of the electron density differences within the $C_4H_{10}O_2S_2$ molecule (g), AgNWs (h) and $C_4H_{10}O_2S_2$ -Ag (i).

Multi-scenario adaptability in smart electronics strictly demands exceptional EMI shielding performance. A comparison of EMI SE between PNF films and M-AgNWs/PNF composites across the X-band (8.2–12.4 GHz) is depicted in Fig. 2(b). Owing to the inherently insulating nature of PNF films, electromagnetic waves (EMWs) can penetrate without attenuation yielding an EMI SE near 0 dB due to the absence of reflection or absorption [49-51]. Conversely, increasing the M-AgNWs content substantially enhance EMI SE of M-AgNWs/PNF composite films, surging from 22 dB at 10 wt% to an outstanding 81 dB at 50 wt%. This performance leap is driven by the construction of an interconnected conductive network. Within this framework, incident EMWs is strongly reflected by intense free-electron oscillations, while the remaining energy is further dissipated via interfacial polarization and ohmic losses, culminating in a superior shielding effect. Fig. 2(c) delineates the contributions of absorption efficiency (SE_A) and reflection efficiency (SE_R) to the total shielding efficiency (SE_T) of M-AgNWs/PNF composite films. Notably, both SE_A and SE_R exhibit an upward trend with increasing M-AgNWs mass fraction, with SE_A consistently and significantly surpassing SE_R . Specifically, a dramatic boost from 16 to 64 dB is observed for the SE_A value when the M-AgNWs content increases from 10 wt% to 50 wt%, contrastingly, SE_R only exhibits a marginal growth from 6 to 17 dB. Upon impinging on the surface of M-AgNWs/PNF composite films, the incident EMWs encounter a severe impedance mismatch with air due to the high σ of the AgNWs, triggering a strong primary reflection at the interface. Concurrently, the portion of EMWs that penetrates into M-AgNWs/PNF composite films interior interacts intensely with the interconnected M-AgNWs/PNF conductive network. This architecture efficiently dissipates the remaining electromagnetic energy through ohmic losses and multiple internal reflections, thereby endowing the composite films with exceptional wave attenuation capabilities [52-54].

Practical deployment in harsh and complex environments demand exceptional reliability from EMI shielding composites [55-57]. Therefore, long-term aging and chemical tolerance tests are performed to evaluate the environmental durability of M-AgNWs/PNF composite films. Fig. 2(d) evaluates the EMI SE of M-AgNWs/PNF composite films immersed in different chemical solutions (HCl, NaOH, NaCl, and organic solutions). Although the EMI SE of each sample decreases slightly post-immersion, it remains at a high shielding level. Notably, the EMI SE dropped to only 73 dB in the acidic solution, indicating that M-AgNWs/PNF composite films can preserve their superior shielding capability in harsh chemical

environments. This confirms the excellent liquid corrosion resistance and environmental adaptability of M-AgNWs/PNF composite films. The aging behavior of M-AgNWs/PNF composite films stored in air for one month is illustrated in Fig. S4(b). Over this prolonged period, M-AgNWs/PNF composite films maintain a highly stable shielding level, with the EMI SE staying well around 75 dB despite a slight initial drop. This highlights the outstanding anti-oxidation capability and environmental durability of AgNWs/PNF composite films. The fact that its EMI shielding performance undergoes negligible decay under ambient conditions underscores its great potential for reliable, long-term practical applications. The EMI SE of M-AgNWs/PNF composite films is benchmarked against recently reported literature data in Fig. 2(f), with detailed comparisons available in Table S1. The EMI SE of M-AgNWs/PNF composite films are higher than ANF/MXene-PEDOT:PSS films (0.047 mm, 63 dB) and MXene/PI films (0.11 mm, 35 dB). By optimizing the trade-off between minimum thickness and maximum shielding effectiveness, M-AgNWs/PNF composite films provide a compelling solution for high-performance electronics, showing significant advantages in the field of lightweight and thin electromagnetic shielding [58, 59].

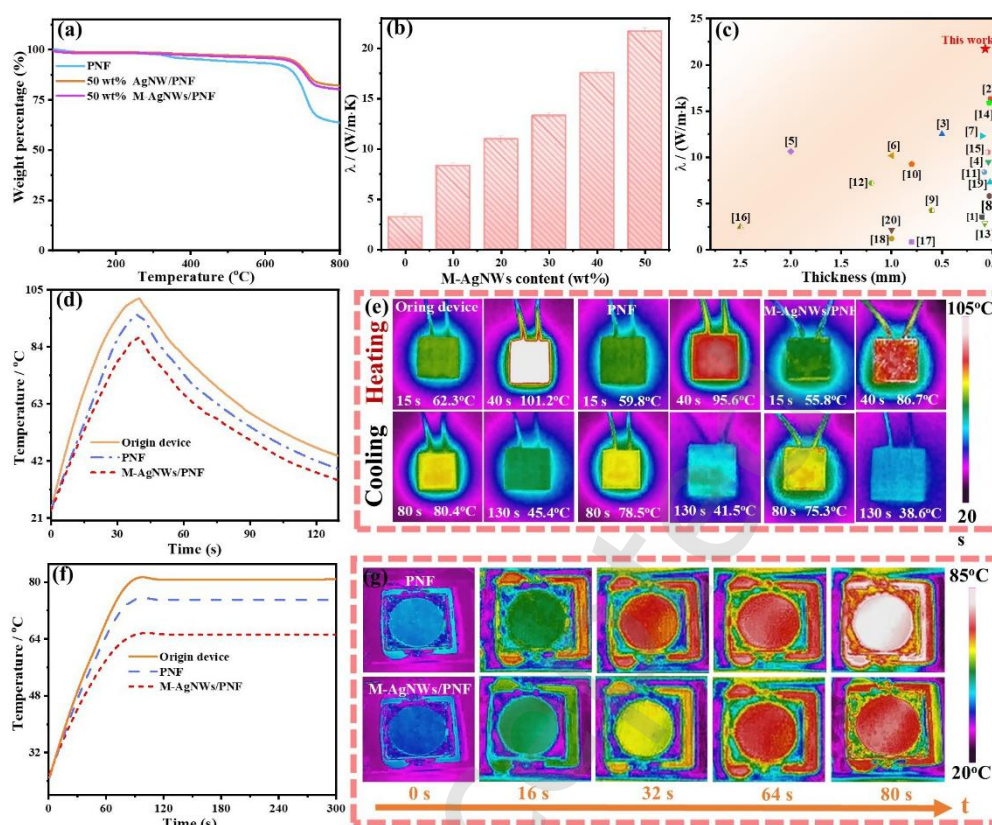
Fig. 2(e) and Fig. S4(c) illustrate the practical feasibility of M-AgNWs/PNF composite films for electromagnetic radiation protection. During mobile phone operation, it emits an electromagnetic radiation intensity of 0.64 μ T, setting off a radiation alarm. Upon covering the phone with M-AgNWs/PNF composite films, the radiation drops to 0 μ T, immediately clearing the alarm. Similarly, M-AgNWs/PNF composite films can block the alternating magnetic field of a Tesla coil; Without shielding, the coil wirelessly powers and illuminates an LED, whereas inserting M-AgNWs/PNF composite films interrupts the energy transfer and turns off the LED. These results confirm the excellent electromagnetic shielding capability for versatile device-level protection.

The evolution of the interfacial electronic structures for $C_4H_{10}O_2S_2$, AgNWs and M-AgNWs is elucidated by the differential charge density derived from First-principles DFT calculations (Fig. 2(g)-2(i)). Specifically, $C_4H_{10}O_2S_2$ molecule shows a remarkable intrinsic polarization feature (Fig. 2(g)), in which O atoms (+1.11 e^-) act as strong electron attractors, whereas S (-0.18 e^-) and C (-0.32 e^-) atoms experience localized electron depletion, establishing a distinct dipole profile. In sharp contrast, AgNWs exhibits a highly symmetrical and periodic charge density distribution, indicative of characteristic metallic delocalized electrons and a homogeneous electrostatic potential field (Fig. 2(h)). Upon the chemisorption of $C_4H_{10}O_2S_2$ on AgNWs surface (Fig. 2(i)), a pronounced interfacial charge rearrangement takes place: evident charge transfer is observed at the Ag atoms (-0.2 e^-), while the intra-molecular charge distribution of $C_4H_{10}O_2S_2$

fluctuates violently (the charge of O atoms is modulated from $+1.11 e^-$ to $+0.11 e^-$, and H atoms exhibit $-0.58 e^-$). This arises from two synergistic electronic mechanisms. For one thing, the sulfur atom in HEDS possesses lone electron pairs with strong electron-donating capability, while the unoccupied d orbitals of surface Ag atoms on AgNWs serve as effective electron acceptors. A coordinative Ag-S bond thus forms, enabling directional charge transfer from S to Ag. For another, upon HEDS adsorption, substantial charge redistribution occurs within the AgNWs-HEDS interface, significantly lowering the charge-transfer energy barrier across the S-Ag junction. Crucially, this interfacial electron transfer is governed by energetic alignment, specifically the matching between the electron-donating capacity of the S lone pairs and the Ag vacant d-orbital acceptor states, whereas the associated charge redistribution induced by Ag-S bond formation kinetically promotes the overall process. Such robust interfacial electronic interactions not only substantiate the chemisorption process but also induce a powerful polarization response along the Z-axis. This interfacial charge redistribution and the resulting polarization enhancement within M-AgNWs substantially reinforce the interfacial polarization loss and heighten the local migration potential barriers for charge carriers. As a result, the incident electromagnetic energy can be effectively dissipated as heat or attenuated through reflection when interacting with incoming electromagnetic waves, ultimately imparting outstanding EMI shielding effectiveness to the M-AgNWs/PNF composite films.

3.3 Evaluation of thermal conductivity for M-AgNWs/PNF films

The TGA curves confirm the excellent thermal stability of PNF films, AgNWs/PNF and M-AgNWs/PNF composite films (Fig. 3(a)). The results show that they exhibit excellent thermal stability. Below 640°C , PNF films undergo only marginal weight loss. Beyond this onset temperature of 640°C , a significant weight reduction is observed across all three samples. This weight loss is primarily driven by the high-temperature carbonization of the organic PNF framework. Evidently, M-AgNWs/PNF composite films experience noticeably less mass reduction than PNF films. This enhanced thermal resistance stems from the fact that the inorganic AgNWs is thermally stable within this temperature range and act as an effective physical barrier, thereby retarding the escape of volatile decomposition products. Notably, the overall



similarity in TGA between M-AgNWs/PNF and AgNWs/PNF composite films indicate that HEDS surface modification leaves the thermal stability of AgNWs unimpaired.

Figure 3 (a) TGA curves of PNF films, AgNWs/PNF composite films, and M-AgNWs/PNF composite films. (b) The λ of M-AgNWs/PNF composite films. (c) Comparison of λ between M-AgNWs/PNF composite films and previously reported works. (d) The temperature variation over time of heating resistance in air, PNF films, M-AgNWs/PNF composite films, and (e) corresponding infrared thermal images. (f) The temperature variation over time of CPU in air, PNF films, M-AgNWs/PNF composite films, and (g) corresponding infrared thermal images.

Upon prolonged exposure to electromagnetic radiation, electronic devices frequently suffer from substantial heat generation and subsequent thermal stress. The variations in λ for M-AgNWs/PNF composite films is displayed in Fig. 3(b). Driven by the progressive addition of M-AgNWs, the λ value exhibits a continuous growth. PNF films possess a mere λ of 3.2 W/(m·K), which is restricted by the low intrinsic thermal conductivity of the polymer matrix. Notably, shifting the M-AgNWs content from 10 wt% to 50 wt% leads to a substantial enhancement in the λ of M-AgNWs/PNF composite films, rising from 8.3 W/(m·K) to 21.7 W/(m·K). Fundamentally, the inherent high thermal conductivity of AgNWs, combined

with the interlocking and overlapping of high-aspect-ratio nanowires within PNF, constructs a continuous conductive network that facilitates rapid phonon transport. Microscopically, at the microscopic level, Ag-S coordination bonds and interfacial hydrogen bonds enhance phonon density-of-states matching and synergistically lower interface thermal resistance. Under higher loads, the denser overlap of M-AgNWs further minimizes interface thermal resistance, promoting localized heat transfer and conferring superior thermal conductivity to M-AgNWs/PNF composite films. A comparison of λ between M-AgNWs/PNF composite films and recently documented counterparts is illustrated in Fig. 3(c), with detailed parameters summarized in Table S2. The comparison clarifies the distinct advantages of M-AgNWs/PNF composite films in integrating high thermal conductivity with structural thinness. Remarkably, M-AgNWs/PNF composite films exhibit a superior λ of 21.7 W/(m K) at a thickness of 0.07 mm, outperforming typical counterparts like the 0.08 mm PI/BNNS/CNT@PVA film ($\lambda=8.4$ W/(m K)) and the 0.1 mm FG/PNF film ($\lambda=12.3$ W/(m K)).

As the power density of electronic devices consistently rises, severe heat dissipation issues have emerged as a primary threat to their operational performance, reliability, and lifespan. The thermal management efficiency of M-AgNWs/PNF composite films are assessed using heating resistors and computer CPU. Fig. 3(d) illustrates the transient surface temperature changes of the bare resistor and the resistors integrated with PNF films and M-AgNWs/PNF composite films, which are visually corroborated by the infrared thermal images in Fig. 3(e). Without a heat sink or when covered by PNF films, the resistor attains high temperatures of 101.9°C and 96.5°C after 40 s of operation, respectively. However, when M-AgNWs/PNF composite films are deployed as the heat dissipation layer, the surface temperature of the resistor significantly suppressed to 87.6°C. This contrast firmly confirms that M-AgNWs/PNF composite films can effectively mitigate the accumulated heat generated during operation. Furthermore, corresponding infrared thermograms confirm a uniform thermal distribution across M-AgNWs/PNF composite films surface throughout both heating and cooling processes. In CPU thermal management tests (Fig. 3(f)-3(g)), the peak surface temperature of the CPU equipped with M-AgNWs/PNF composite films reach only 65.2°C after 90 s, contrastingly lower than the 81.3°C for air and 75.4°C for PNF films heat sinks. Meanwhile, the infrared thermograms exhibit a well-distributed temperature field, which validates that M-AgNWs/PNF composite films possess enhanced thermal conductivity relative to PNF and can successfully prevent hotspots. Furthermore, flammability evaluations (Fig. S5) show that exposing PNF films and M-AgNWs/PNF composite films to a flame for 10 s causes only slight shrinking. After flame removal, no

residual flaming or smoking is detected for over 30 s, and their original shapes are largely preserved. It confirms that the exceptional flame-retardancy of M-AgNWs/PNF composite films renders them highly promising candidates for advanced electronic thermal management [60, 61].

3.4 Photothermal conversion performance of M-AgNWs/PNF composite films

As a clean, cost-effective, and renewable resource, solar energy serves as a prime candidate for harnessing power through light-to-heat conversion pathways. Fig. 4(a) compares the optical absorption paths of PNF films and M-AgNWs/PNF composites across the UV-vis-NIR spectrum. In the UV range, both matrices manifest prominent absorption bands with nearly identical tracks and high intensity, confirming their similar UV-light trapping efficiency. Subsequently, a rapid drop-off in absorbance is captured for both specimens with increasing wavelength into the visible zone. Benefiting from the AgNWs-induced localized surface plasmon resonance (LSPR) phenomenon, the LSPR phenomenon generates intense electromagnetic field confinement in the vicinity of AgNWs, markedly improving the NIR photon harvesting efficiency of M-AgNWs/PNF composite films. Following surface functionalization with HEDS, AgNWs achieve uniform dispersion within PNF and self-assemble into a percolating, hierarchically ordered conductive and thermally conductive network. This structural architecture not only promotes efficient charge carrier and phonon transport, but critically enables coherent spatial coupling and collective enhancement of LSPR responses across AgNWs ensemble, thereby yielding broadband, macroscopically amplified plasmonic absorption in the NIR regime. By contrast, PNF films exhibit negligible NIR absorption, as their optical response stems solely from weak, narrowband intramolecular electronic transitions, which are energetically mismatched with NIR photons. M-AgNWs/PNF composite films display significantly enhanced absorbance in the near-infrared region compared to pristine PNF films, thereby validating their superior light-harvesting performance.

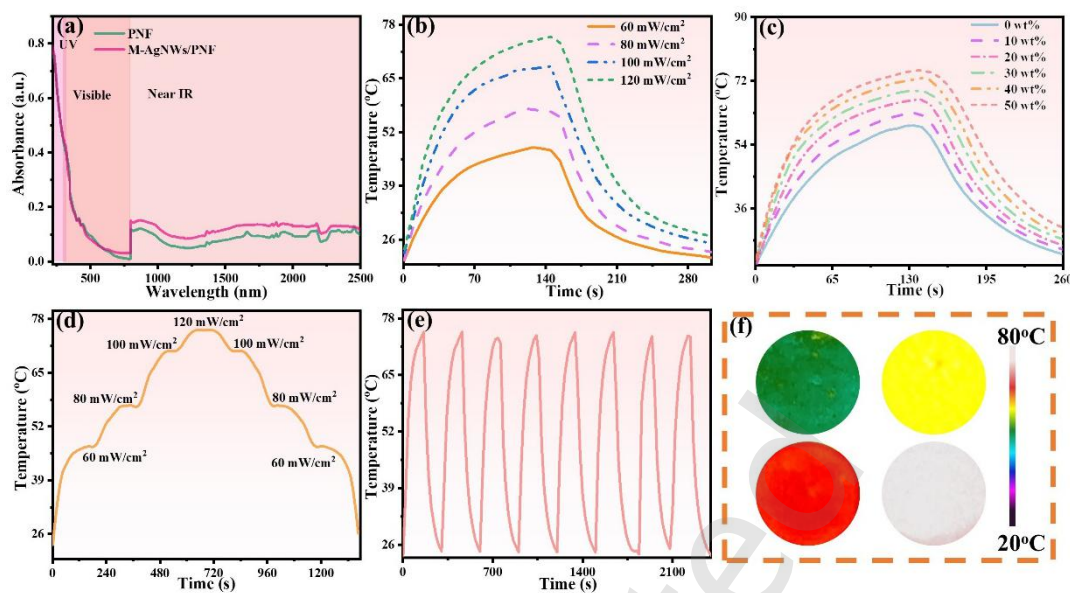


Figure 4 (a) UV-Vis-NIR absorption spectra of PNF films and M-AgNWs/PNF composite films. (b) Surface temperatures of PNF films and 50 wt% M-AgNWs/PNF composite films under various optical power densities (60, 80, 100 and 120 mW/cm²) and (f) corresponding infrared thermal images. (c) Surface temperatures of M-AgNWs/PNF composite films with varying M-AgNWs contents under a light intensity of 120 mW/cm². (d) Tailored surface temperature upon gradient changed the light density of M-AgNWs/PNF composite films. (e) Heating stability and repeatability of M-AgNWs/PNF composite films.

Developing materials with efficient photothermal conversion properties that can effectively convert solar energy into thermal energy will greatly expand their general application in cold environments. Fig. 4(b) depicts the photothermal scaling behavior of 50 wt% M-AgNWs/PNF composite film across a range of incident light intensities (60-120 mW/cm²). The sharp temperature rise under illumination underlines the robust capacity of the network to intercept and localize photons into thermal energy. Due to the increased photon flux at higher power densities, the stable high temperature climbs from 47.6°C at 60 mW/cm² to 75.1°C at 120 mW/cm². The corresponding infrared thermal images (Fig. 4(d)) confirm excellent spatial heat uniformity, as indicated by the well-distributed, consistent color profiles. Crucially, M-AgNWs/PNF composite films exhibit an agile photothermal response. Diverse simulated solar flux densities can drive the material to its thermal saturation point very rapidly; this quick attainment of equilibrium makes it an optimal candidate for dynamic light-to-heat conversion.

The surface temperature profiles of M-AgNWs/PNF composite films recorded under an illumination of 120 mW/cm² are displayed in Fig. 4(c). The introduction of M-AgNWs triggers a distinct upward shift in photothermal properties, correlating positively with the filler density. The temperature ceiling transitions

from a modest 59.3°C for PNF films to 62.9°C at 10 wt%, ultimately reaching 74.8°C at 50 wt%. This step-wise improvement is driven by the enhanced interfacial affinity between the functionalized M-AgNWs and the host PNF, ensuring uniform filler dispersion and creating robust phonon transport pathways. Ultimately, a dual-action mechanism is achieved: The intense LSPR effect of AgNWs guarantees efficient localized photon trapping, while the well-engineered thermal network provides a highway for rapid heat diffusion, creating a powerful multiscale synergy that maximizes solar-thermal conversion.

As illustrated in Fig. 4(d), upon cyclically tuning the optical power density within a gradient range of 60-120 mW/cm², the peak surface temperature of M-AgNWs/PNF composite films shifts rapidly, which verifies a highly sensitive and adjustable photothermal conversion capability. To assess their long-term durability, M-AgNWs/PNF composite films are subjected to multiple simulated solar on/off switches (Fig. 4(e)). Throughout 8 continuous operational loops, the temperature ceiling remains firmly at 74.8°C, demonstrating superb photothermal fatigue resistance and structural reversibility under cyclic thermal stress.

3.5 Joule heating profiles of M-AgNWs/PNF composite films

The excellent Joule heating performance enables the material to achieve rapid and controllable electro-thermal conversion upon electrification, thereby autonomously regulating heat generation to match actual thermal load requirements. Fig. 5(a) illustrates the Joule heating curve of PNF films and M-AgNWs/PNF composite films. Owing to its insulating nature, PNF film remains at a room temperature of 22.7°C even under 3.5 V. In contrast, by expanding M-AgNWs loading from 10 wt% to 50 wt%, the equilibrium thermal readout of M-AgNWs/PNF composite films undergoes a dramatic boost from 35.8°C to 79.4°C.

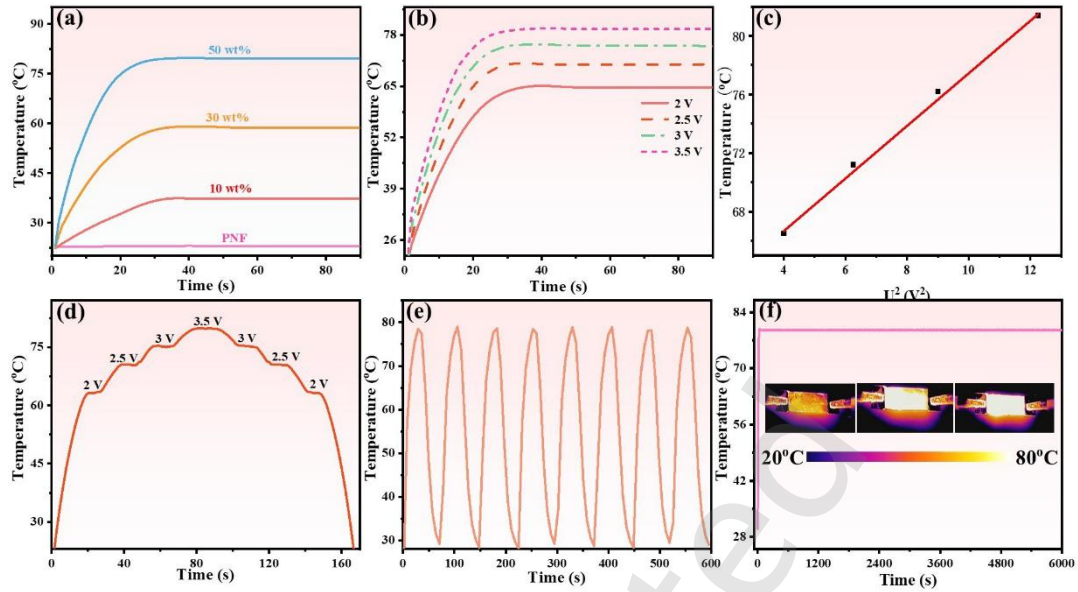


Figure 5 (a) Joule heating performance of PNF films and M-AgNWs/PNF composite films. (b) The electrothermal conversion performance of M-AgNWs/PNF composite films under changing voltages. (c) Linear fitting of surface temperature and U^2 . (d) Surface temperature vs voltage of M-AgNWs/PNF composite films. Long-term stability and reliability of M-AgNWs/PNF composite films at (e) repeated and (f) constant voltages of 2 V.

Fig. 5(b) presents the Joule heating performance of M-AgNWs/PNF composite films under different voltages. A monotonic voltage-dependent temperature rise is observed for M-AgNWs/PNF composite films, which swiftly stabilizes into a thermal equilibrium, highlighting an agile electro-thermal response and a highly efficient Joule heating capability. Within a brief span of 30 s under a 2 V, M-AgNWs/PNF composite films exhibit an impressive temperature leap from ambient conditions to 64.6°C. When the voltage is further increased to 3.5 V, the temperature rapidly surges to 79.5°C within the same time frame. Furthermore, Fig. 5(c) shows the linear regression fitting of the steady-state surface temperature for M-AgNWs/PNF composite films against the square of the voltage (U^2). The outstanding linear relationship between the stable temperature and U^2 directly confirms the validity of Joule's law.

Fig. 5(d) illustrates the relationship between the supreme surface temperature of M-AgNWs/PNF composite films and the applied voltage. Under stepwise voltage changes, M-AgNWs/PNF composite films deliver a rapid temperature response with negligible lag, demonstrating great promise for smart thermal management. To assess their long-term durability and reliability, cyclic heating/cooling and extended stability tests are performed at 3.5 V (Fig. 5(e)-5(f)). The temperature responds predictably to the voltage adjustments, showcasing typical Joule heating characteristics alongside superb controllability and

repeatability. During consecutive on-off cycles, M-AgNWs/PNF composite films swiftly return to the same steady-state temperature after each power-on, yielding highly reproducible and overlapping temperature curves without noticeable decay or fluctuations.

3.6 Mechanical performance of M-AgNWs/PNF composite films

Superior mechanical characteristics endow EMI shielding materials with high load-bearing capability, flexibility under deformation, and excellent fracture toughness without sacrificing shielding efficiency. Consequently, this maintains their structural integrity and ensures long-term reliability in complex environments. As demonstrated by the tensile profiles in Fig. 6(a) and Fig. S6, the reinforcement effect of M-AgNWs on PNF is highly concentration dependent. Pure PNF possesses a tensile strength of 117.9 MPa and a 1.28% fracture strain. With growing M-AgNWs contents, the mechanical indices first climb and then drop, which is governed by the interplay between two competing mechanisms: interfacial strengthening and agglomeration induced stress concentration. At low filler loadings, interfacial strengthening predominates, leading to enhanced mechanical performance; conversely, at high filler loadings, agglomeration-induced stress concentration becomes dominant, resulting in mechanical property degradation. The most distinct reinforcement is spotted at 20 wt% loading, where the composite film demonstrates an exceptional tensile strength of 181.4 MPa (boasting a 33.1% enhancement over the neat PNF) and a failure strain expanded to 1.51%. This reinforcement benefits from HEDS molecules anchored on AgNWs via Ag-S coordination, whose terminal hydroxyl groups form extensive hydrogen bonds with PNF to bolster interfacial adhesion. Additionally, the high aspect ratio of AgNWs promotes efficient load transfer across the well-bonded interface. Conversely, an excessive M-AgNWs loading of 50 wt% exerts a detrimental effect on the material, causing the tensile strength to drop down to 101.3 MPa. Elevated M-AgNWs loading triggers localized agglomeration within PNF, creating stress concentration centers. This disrupts the structural uniformity of M-AgNWs/PNF composite films and impedes stress transfer, ultimately deteriorating both tensile strength and elongation at break.

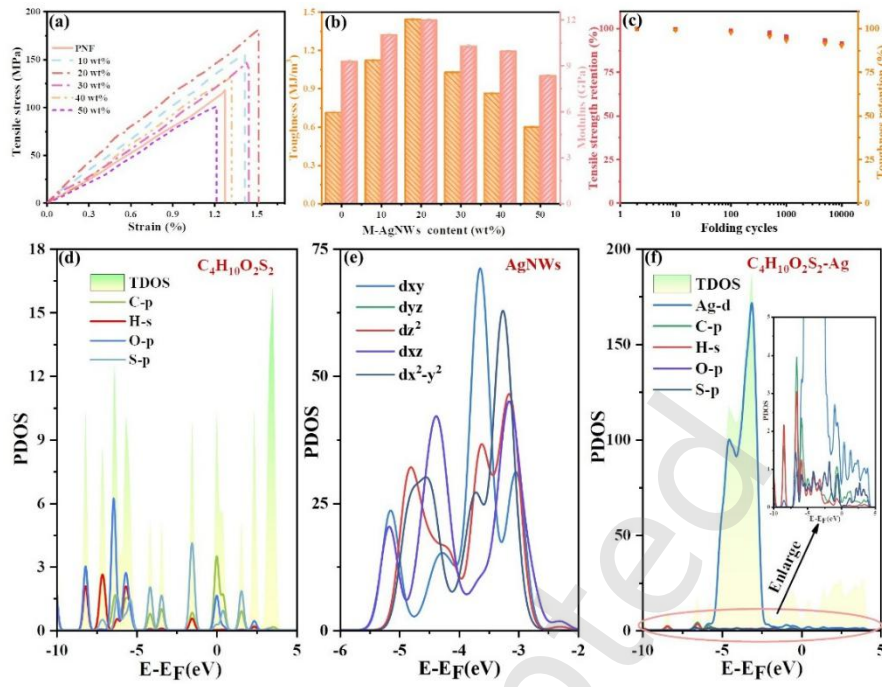


Figure 6 (a) Tensile stress-strain curves, (b) modulus and toughness of M-AgNWs/PNF composite films. (c) Tensile strength and toughness of M-AgNWs/PNF composite films after multiple folds. The partial density of states (PDOS) for the internal $C_4H_{10}O_2S_2$ molecule (d), AgNWs (e), and the $C_4H_{10}O_2S_2$ -Ag interface.

As demonstrated by the mechanical metrics in Fig. 6(b), PNF films exhibit a modulus of 9.28 GPa and a toughness of 0.71 MJ/m³. Tuning the M-AgNWs dosage within 10 wt%-50 wt% triggers a biphasic response in M-AgNWs/PNF composite films of toughness: it initially intensifies from 1.12 MJ/m³ to a peak threshold of 1.44 MJ/m³, but ultimately retreats to 0.60 MJ/m³. Similarly, the modulus follows a matching trajectory, escalating from 11.02 GPa to 11.98 GPa and subsequently decreasing to 8.34 GPa.

The mechanical durability of M-AgNWs/PNF composite films is further highlighted in their tensile strength and toughness tests (Fig. 6(c)). Remarkably, 20 wt% M-AgNWs/PNF composite films sustain 91.56% of its tensile strength and 90.43% of its toughness even after 10,000 folding cycles. This superior anti-fatigue attribute is ascribed to a synergistic effect: the HEDS modification implants dense polar functional groups on AgNWs surfaces to drastically boost interfacial adhesion with PNF matrix, while the reversible cleavage-regeneration of dynamic disulfide (S-S) bonds empowers the conductive and thermal networks to dissipate energy and self-heal under cyclic deformation, effectively mitigating microcrack nucleation and propagation.

Fig. 6(d)-6(f) exhibits the differential charge density of states (PDOS) of $C_4H_{10}O_2S_2$, AgNWs, and M-AgNWs obtained from DFT calculations. The electronic states of $C_4H_{10}O_2S_2$ mainly concentrate covering the energy spectrum from -10 eV to -3 eV, whereas the density of states near the Fermi level ($E-E_F$) is

extremely low (Fig. 6(d)). Fig. 6(e) shows that AgNWs possess a significant the Fermi-level density of states, which is a typical manifestation of metallic characteristics, indicating a large number of freely movable electrons. After modification with $C_4H_{10}O_2S_2$, distinct hybridization peaks appear in the PDOS of M-AgNWs within the range of 2~4 eV. This hybridization peak originates from the strong resonance and electron cloud overlap between the Ag d-orbital and the S p-orbital, confirming that $C_4H_{10}O_2S_2$ is chemically adsorbed on the AgNWs surface through Ag-S coordination rather than mere physical adsorption. Consequently, the M-AgNWs surface becomes profuse -OH groups, which improves the dispersibility of AgNWs within the PNF, thereby verifying that the modification of AgNWs with $C_4H_{10}O_2S_2$ can enhance the mechanical properties of the PNF films.

4 Conclusions

Herein, by synergizing the polyol method and Ag-S coordination with vacuum-assisted filtration and hot-pressing techniques, flexible multifunctional M-AgNWs/PNF composite films are efficiently constructed. The embedded AgNWs, characterized by high conductivity and a large aspect ratio, forms interconnected networks within PNF, facilitating rapid electron and phonon transmission. With M-AgNWs fraction fixed at 50 wt%, M-AgNWs/PNF composite films achieve σ of 4545 S/cm and λ of 21.7 W/(m·K), and EMI SE of 81 dB, and their tensile strength is adjustable between 101.3 and 181.1 MPa. DFT simulation results confirm that HEDS adsorbs onto AgNWs through Ag-S coordination, and the functionalized M-AgNWs can form efficient electrically and thermally conductive networks within PNF, thereby elevating the EMI shielding effectiveness while simultaneously reinforcing the structural integrity of the M-AgNWs/PNF composite films. Additionally, M-AgNWs/PNF composite films exhibit outstanding photothermal and Joule heating capabilities. The surface temperature spikes to 74.8°C under 120 mW/cm² simulated solar light and to 79.4°C under a 3.5 V voltage. This strategy opens new avenues for fabricating flexible, lightweight, and multifunctional EMI shielding materials for next-generation integrated electronics and aerospace applications. Subsequent research will prioritize the optimization of the manufacturing process to enhance scalability, cost-effectiveness, and performance, specifically electromagnetic shielding effectiveness and mechanical robustness. Furthermore, a comprehensive long-term stability evaluation will be carried out under representative service conditions, including elevated temperature, high relative humidity, and cyclic mechanical loading, to rigorously validate reliability and durability in practical engineering deployment.

Supplementary data

Supplementary data to this article can be found online.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 52303090); The Science and Technology Innovation Team Project of Shaanxi Province (2025RS-CXTD-040); The Youth Talent Promotion Project of Shaanxi Science and Technology Association (No. 20240426); The Doctor Research Start Foundation of Shaanxi University of Technology (SLGRCQD039); The authors extend their gratitude to Shiyanjia Lab (www.shiyanjia.com) for providing invaluable assistance with the XPS and SEM analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

X. B. X.: Writing-original draft, Data curation. W. N. R.: Writing-review & editing. H. C. L. and Y. R. Z.: Data curation, Partial material characterization. W. Z. T.: Data curation, Validation. Y. Z. L.: Supervision and Investigation. L. W.: Writing-review & editing, Methodology.

Use of AI statement

None.

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Electronic Supplementary Material

Multifunctional folding-endurance poly(p-phenylene benzobisoxazole) nanofibers composite films for remarkable electromagnetic interference shielding and thermal management

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Supporting information to <https://doi.org/10.26599/NR.2026.94909084>

Supplementary Figures

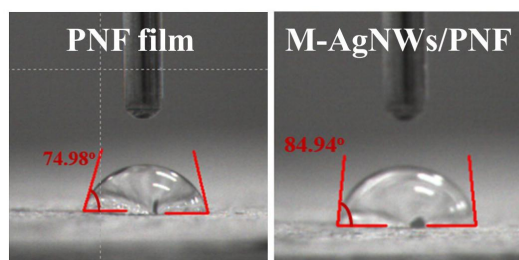


Figure S1 Contact angles of PNF films and M-AgNWs/PNF composite films.

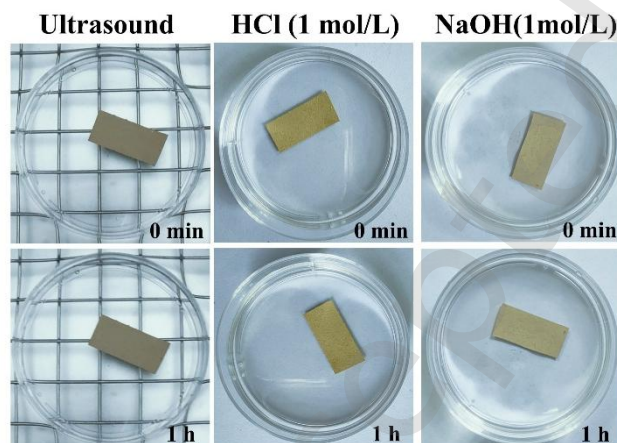


Figure S2 M-AgNWs/PNF composite films (a) under ultrasonication, (b) in 1mol/mL HCl and (c) 1mol/mL NaOH for 30 min.

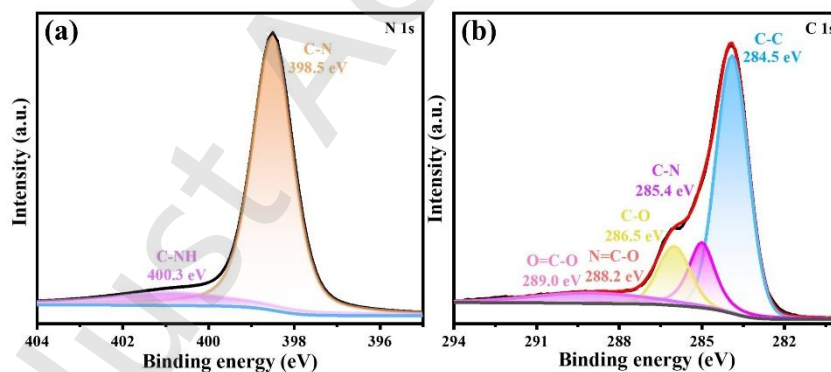


Figure S3 N 1s and C 1s spectra of M-AgNWs/PNF composite films.

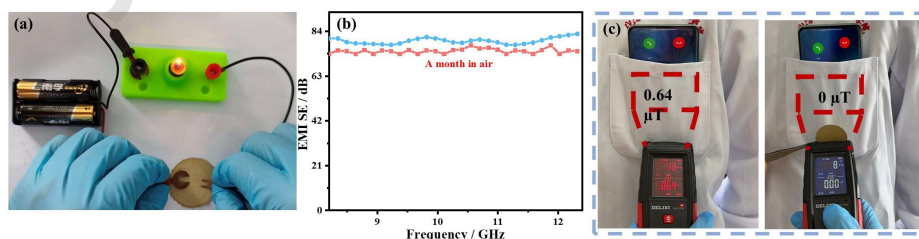


Figure S4 (a) Experimental setup for testing the electrical conductivity of M-AgNWs/PNF composite films. (b) EMI SE of M-AgNWs/PNF composite films before and after ambient air storage for one month. (c) EMI shielding evaluations of M-AgNWs/PNF composite films blocking mobile phone signals.

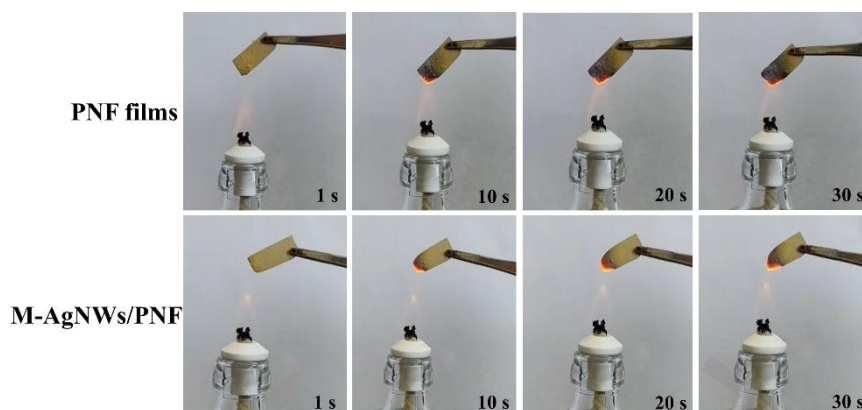


Figure S5 Optical photos of PNF films and M-AgNWs/PNF composite films during combustion.

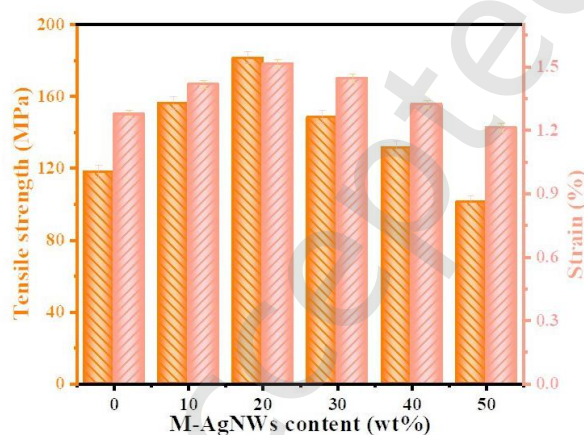


Figure S6 Tensile strength and strain of M-AgNWs/PNF composite films.

Table S1. Comparison of EMI shielding performance of M-AgNWs/PNF composite film with other works

Sample	Thickness (mm)	EMI SE (dB)	Ref.
ANF/MXene-PEDOT:PSS	0.047	63	[1]
PVDF/MWCNTs/GO@MWCNTs/AgNWs	0.47	69	[2]
Ti ₃ C ₂ T _x MXene/PI	0.11	34	[3]
Graphene/PEDOT:PSS	0.02	54	[4]
CF@NiCo/PI	0.2	40	[5]
PEDOT:PSS/Li-TFSI/XSB	0.2	50	[6]
PEG/PEDOT:PSS@cotton fabric	0.38	46	[7]
MXene/wood	0.38	33	[8]
PVDF/MXene/AgNW	0.6	41	[9]
CNF/rGO/Fe ₃ O ₄	0.5	40	[10]
MXene/PI	0.11	35	[11]
PS/CNT/PEDOT:PSS	0.6	22	[12]
PANI/MXene	0.37	35	[13]
Graphene/WPU	0.15	30	[14]

Li-TFSI doped PEDOT:PSS	0.2	30	[15]
PEDOT:PSS/BC	0.28	72	[16]
PVDF/MXene/Ni	0.36	34	[17]
Carbon fabric@CoFe/PI	0.98	42	[18]
PANI-PS-GO	0.85	40	[19]
CNT/paper/TPU	0.54	69	[20]
M-AgNWs/PNF	0.07	79	This work

Table S2. Comparison of λ of ALAFS with other works

Sample	Thickness (mm)	λ (W/m·k)	Ref.
V ₂ O ₅ @NaV ₆ O ₁₅ @PPyCSNFs	0.1	3.56	[21]
BNNS/PVDF	0.018	16.3	[22]
EMPI@VACNTs	0.5	12.5	[23]
ITBCF	0.039	9.49	[24]
HO-BNNS@Fe ₃ O ₄	2	10.64	[25]
EO/GR	1	10.17	[26]
FG/PNF	0.1	12.30	[27]
Ti ₃ C ₂ T _x /PNF	0.03	5.82	[28]
PDMS/f-C@BNNS	0.60	4.26	[29]
MXene/graphene	0.8	9.26	[30]
PI/BNNS/CNT@ α PVA	0.08	8.40	[31]
SABPA/EG-DBN PCM	1.2	7.21	[32]
(Fe ₃ O ₄ /Ti ₃ C ₂ T _x)/PVA	0.075	2.86	[33]
ALAFS	0.03	15.9	[34]
AgNWs/cellulose	0.0445	10.55	[35]
APCF-epoxy	2.5	2.49	[36]
GNP/PEDOT:PSS	0.8	0.83	[37]
RGO@Fe ₃ O ₄ /epoxy	1	1.2	[38]
RGO/CNF	0.023	7.3	[39]
rGO-WPU/cotton	1	2.13	[40]
M-AgNWs/PNF	0.07	21.71	This work

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