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Supporting Information

All-Organic Flexible Fabric Antenna for Wearable Electronics

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RF sheet resistance measurement

The sheet resistance of the PEDOT: PSS printed fabric was measured in comparison with a copper sheet by using a coaxial probe[1] and a VNA. Sheet resistances for PEDOT:PSS printed fabric and copper measured from 0.5 to 3 GHz are shown in Figure S1. The sheet resistance of the PEDOT: PSS printed fabric is within the same order of magnitude of copper sheet in the gigahertz frequency. This result showed the capability of the conductive fabric for replacing copper sheet in RF devices and applications.

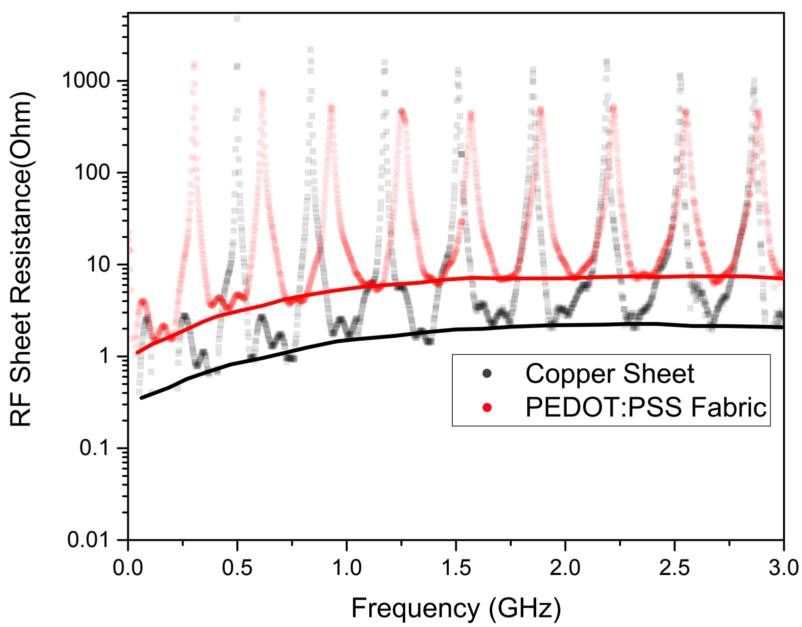

Figure S1. RF sheet resistance comparison between PEDOT:PSS fabric and copper substrate. The dots are measured results with RF resonance and the solid lines indicate effective sheet resistance.

The PEDOT:PSS printed fabric

According to the SEM image in Figure S2, the PEDOT:PSS printed layer can be seen on the left side of the image with a thickness of ~200 µm.

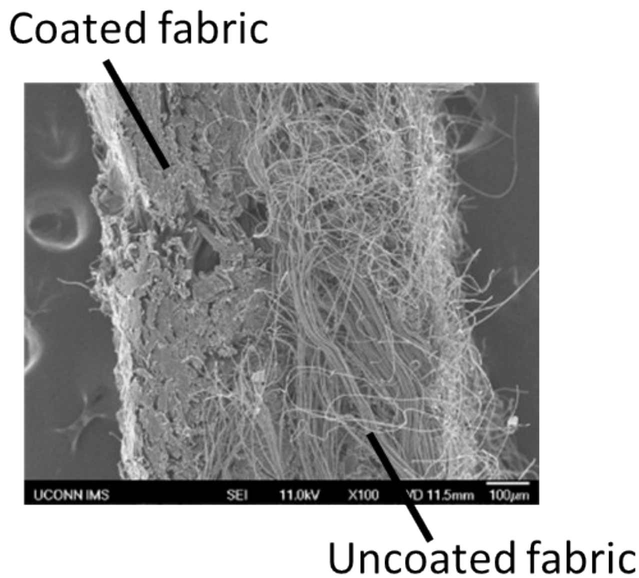

Figure S2. The SEM image of the printed PEDOT:PSS printed fabric

ANSYS HFSS simulation

The size of the antenna was calculated based on standard transmission line model to obtain the desired resonance frequency. ANSYS HFSS was used to simulate the S parameter and far field radiation patterns (Figure S3). The center pin of the SMA connector was fed through the fabric substrate and the position of the feed point was optimized for impedance matching. The far field calculation results are summarized in Table S1.

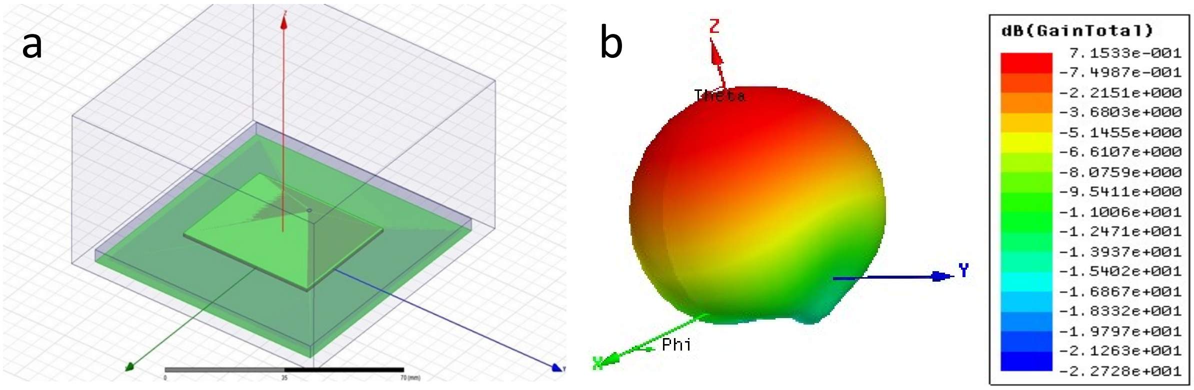

Figure S3. ANSYS HFSS simulation of the PEDOT: PSS printed fabric antenna. a) Model of the fabric antenna in ANSYS HFSS. b) Simulated radiation pattern of the fabric antenna

Table S1: Simulated Performance Parameters of the Patch Antenna

Resonant frequency	**2.39 GHz**
Peak Directivity	4.86 dBi
Peak Gain	1.26 dBi
Radiation Efficiency	25.93%

The replacement of copper and dielectric layer of the patch antenna

A 2.4 GHz patch antenna was fabricated with a Ultralam 2000 microwave substrate with copper sheet electrodes as the reference of the "state-of-art" patch antenna (Figure S4). The dimensions of the substrate and the ground plane were chosen to be 80mm x 80mm. ANSYS HFSS simulation was used to identify the feed point location and to evaluate the performance of the antenna. The VNA return loss result measurement with a 50 Ω input impedance suggests that the resonant frequency of the copper antenna is at 2.35 GHz. The S11 parameter is measured to be -40 dB at the resonant frequency and almost 0 dB elsewhere, which matches well with our original design.

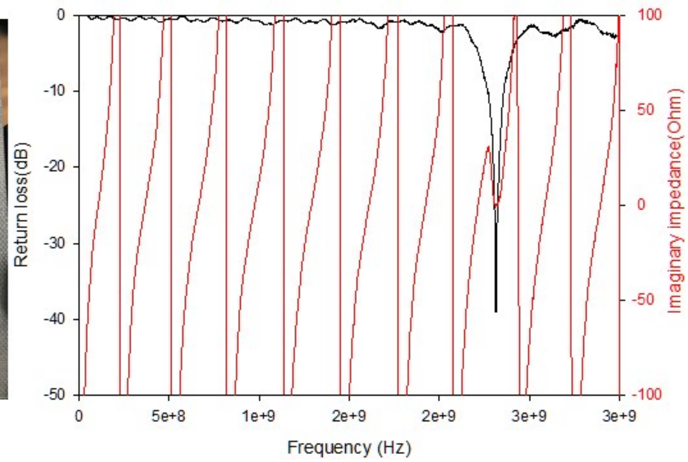

Figure S4. Characterization of the reference copper antenna.

Next, we replaced the copper patch on the original antenna with a piece of PEDOT:PSS printed fabric. The size of the patch was recalculated based on properties of the material, and the feed point location was re-estimated with the help of ANSYS HFSS simulation. The VNA measurement results show that the resonant frequency is still at 2.35 GHz, but a small amount of energy is not returned throughout the scan, indicating there is minor resistive loss in the PEDOT:PSS printed fabric.

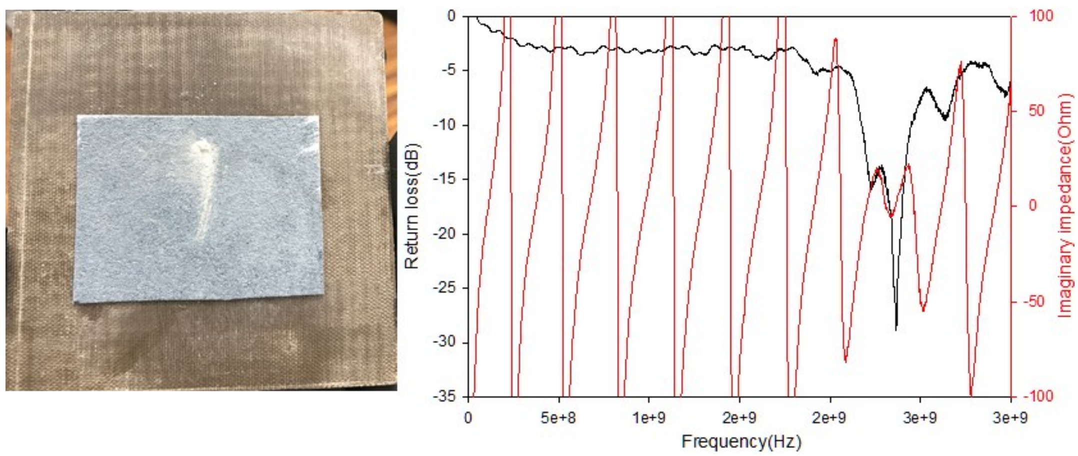

Figure S5. Replacing copper patch with a PEDOT:PSS printed fabric sheet

Next, we made an antenna with copper sheet as conducting layer and PET fabric as dielectric layer to investigate the influence of the fabric as the dielectric layer. The dimensions of the patch were recalculated again based on properties of the material, and the location of the feed point was re-estimated with the help of simulation. The S11 parameter is almost identical with the reference copper patch antenna, indicating that the PET fabric will not introduce extra loss into the device and most of the characteristic stays the same with the reference copper antenna.

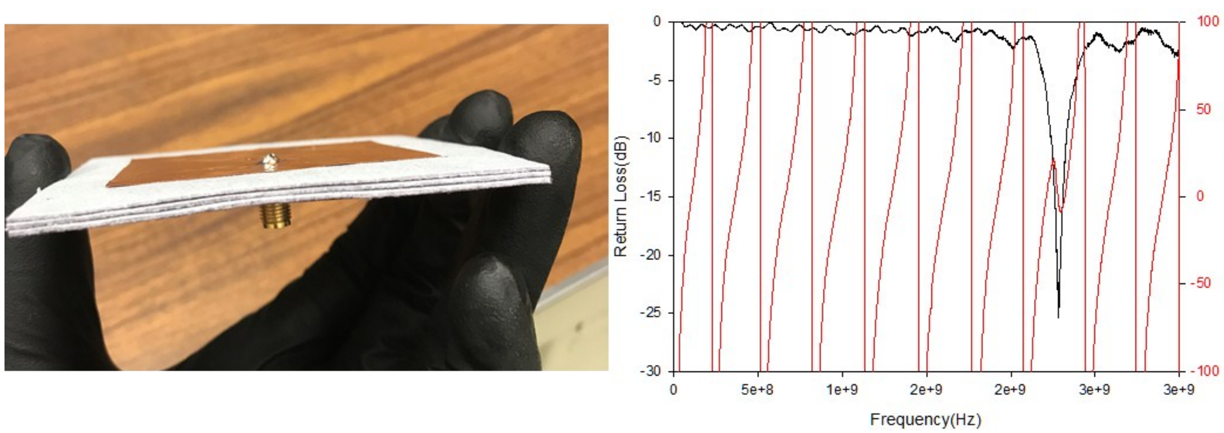

Figure S6. Replacing the Ultram 2000 dielectric substrate with an organic PET fabric

Lastly, an all-organic patch antenna was made with PEDOT:PSS printed fabric, and the characterization can be found in the main context.

Smith Chart

According to the Smith Chart results in Figure S7, the input impedance decreased slightly compared to that of the flat condition, leading to a little higher return loss. These changes on the return loss did not diminish the performance of the antenna.

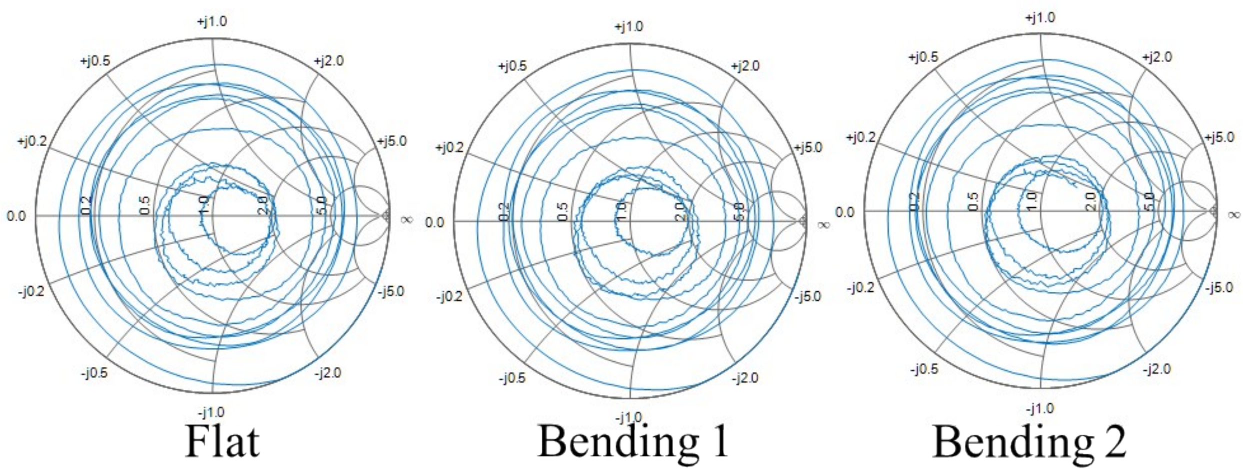

Figure S7. Smith chart for the measurement under various flexed conditions.

Performance Comparison

Table S2. Performance Comparison

	RF sheet resistance	Antenna return loss at 2.4 GHz	Antenna efficiency	Characteristics
PEDOT: PSS printed fabric	6.9 Ω	-54 dB	28%	All-organic wearable
Free standing PEDOT film [2]	N/A	-20 dB	33%	Not integrable with cloth
AgNW PDMS [3]	N/A	-22dB	40%	Metal containing
Copper sheet	2.0 Ω	-32 dB	90%	Rigid metal

Most of the previous work on flexible patch antennas are either based on metal/metal-containing fabrics or based on non-fabric thin films/conventional microwave substrate. The all-organic fabric RF transmitter in this work is realized with the help of nano-template assisted PEDOT:PSS conductive phase segregation, forming a multi-strand wire structure with a high surface area that is similar to high frequency Litz-wire, resulting in an extremely low RF sheet resistance within the same order of cooper.

This work is not trying to beat the conductivity of metal or to make “another” conductive polymer based device. The all-organic conductive fabric shows great novelty and advance in the applications of wearable electronics compared with the existing materials. Combining fabrics with conductive polymer by using a very simple and commercial-style process results in the demonstration of first working fabric antenna and doppler radar.

Reference

1. J.-Y. Chung, N. Nahar, L. Zhang, Y. Bayram, K. Sertel, J. J. I. m. Volakis*, IET Microwaves, Antennas & Propagation*, **2012***, 6*, 371.

2. Chen, S. J., Fumeaux, C., Talemi, P., Chivers, B., & Shepherd, R. (2016, July). Progress in conductive polymer antennas based on free-standing polypyrrole and PEDOT: PSS. In 2016 17th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM) (pp. 1-4). IEEE.

3. L. Song, A. C. Myers, J. J. Adam, Y. Zhu, *ACS Appl. Mater. Interfaces,* **2014**, 6, 6, 4248-4253

List of video demos

Movie S1: The video during the measurement with the doppler radar system