Student Presentations

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Multifunctional Wearable Antennas Enabled by Innovative Flexible Material Systems

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Department of Electrical Engineering
The Pennsylvania State University
Outline

- **Introduction**
  - Project Goals and Objectives
- **Body Worn Antennas**
  - Previous Work
  - Current Work
  - Future Work
- **Conclusion**
The antenna is the crucial component which allows the communication between sensors and other on-body and/or off-body components, such as cell phones and routers.

Requirements for the Antenna Design
- Performance
- Physical Constraints
- Legal Requirements

Challenges
- Size
- Deformation
- Placement
The main goal of this project is to develop cutting edge wearable antenna designs (e.g., low profile, small form-factor, high performance) that combine flexible material system technology (i.e., textile materials) with a capability to support low-power wireless transfer of data collected by on-body medical sensors.

These custom-designed antennas will ensure a robust link between the low-power wearable sensors and other on/off body devices.

New ways to add multifunctional capabilities are currently being investigated in order to provide far superior performance compared with COTS antennas.
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Previous
Ground-breaking
Antenna Designs
Flexible Circularly-Polarized Metasurface-Enabled Wearable Antenna --- Design

An anisotropic metasurface was used to create circularly polarized fields.

The flexible antenna prototype is comprised of polydimethylsiloxane (PDMS) dielectric substrates with silver nanowire (AgNW) conducting layers.

Flexible Metasurface

Fabricated Prototype

Designed by PSU (Prof. Douglas Werner's group), Fabricated by NCSU (Prof. Yong Zhu's group).

Antenna Efficiency ~ 80%

Footprint: 50 mm x 50 mm (0.41 \( \lambda_0 \times 0.41 \lambda_0 \))
Total thickness: 6 mm (0.049 \( \lambda_0 \))
Flexible Circularly-Polarized Metasurface-Enabled Wearable Antenna --- Prototype Comparison

**Input Impedance Measurements**
- Flexible Materials (PDMS/AgNW)
  - Simu.
  - Meas.

- Conventional Materials (PCB/Copper)
  - Simu.
  - Meas.

**Axial Ratio Measurements**
- Flexible Materials (PDMS/AgNW)
  - Simulation
  - Measurement

- Conventional Materials (PCB/Copper)
  - Simulation
  - Measurement
Wearable Rx Antennas with Customized Input Impedance

**Target**: High performance PDMS + silver nanowire (AgNW) enabled flexible antenna custom designed for integration with the radio Receiver (Rx).

**Input Impedance**: Specs require a low resistance with an inductive reactance to match with the impedance of the radio circuits.

**Frequency Band**: 2.4G ISM band.

**Footprint**: 40 mm x 40 mm (0.33 $\lambda_0$ x 0.33 $\lambda_0$)

**Total thickness**: 2 mm (0.016 $\lambda_0$)

No COTS antenna is available that can meet the input impedance requirements of the radio system!

Designed by PSU (Prof. Douglas Werner's group), Fabricated by NCSU (Prof. Yong Zhu's group), and Integrated by Umich (Prof. Wentzloff's group).
Single-band Dual-mode Wearable Patch Antenna

Radiation Pattern in Elevation Plane for On-body Mode

- A good port-to-port isolation (~30 dB) is achieved with both of the two ports matched.
- Good impedance matching is achieved for the two ports at 2.45 GHz.
- The gain for the off-body mode is above 8.0 dBi;
- The gain for the on-body mode is around 6.0 dBi.
The wearable antenna is then placed on the human body to investigate the detuning effect in terms of the S-parameters.

A parametric study was conducted on the distance \( d_{am} \) between the antenna and the body model.

We can see that the antenna impedance matching performance is robust in terms of human body loading.
On-Body Mode Antenna

Antenna Geometry

52.85 x 52.85 x 8.328 mm³
0.42 x 0.42 x 0.067 λ₀³

Realized Gain=1.2 dBi
Length=52.85 mm

Realized Gain=2.61 dBi
Length=86.47 mm

BORG Results

5000 Iterations
On-Body Mode Antenna --- Loading Effects

Cylindrical and rectangular tissue models

250 x 250 x 70 mm³

Separation between the antenna and the tissue model: 2 mm

Return loss comparison between the antenna in free space and when placed on different tissue models.
**Homogenous Human Body Performance**

<table>
<thead>
<tr>
<th>E Field (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 0.4936e+002</td>
</tr>
<tr>
<td>2. 0.672e+002</td>
</tr>
<tr>
<td>3. 0.8584e+002</td>
</tr>
<tr>
<td>4. 0.9456e+002</td>
</tr>
<tr>
<td>5. 0.905e+001</td>
</tr>
<tr>
<td>6. 0.621e+001</td>
</tr>
<tr>
<td>7. 0.11e+001</td>
</tr>
<tr>
<td>8. 0.01e+001</td>
</tr>
<tr>
<td>9. 0.001e+000</td>
</tr>
</tbody>
</table>

- **Body**
  - $\varepsilon_r$ 52.7
  - $\sigma$ (S/m) 1.95
  - Density (kg/m$^3$) 1000

Separation between the antenna and the human tissue model: 2-5 mm

On-Body Mode Antenna --- On-Body Performance
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Linear Polarized Textile Antenna

Material Properties (Textile- Jess Jur’s Group)

- Substrate: \( \varepsilon_r = 1.65 \)
- Conductive Layer: \( \sigma = 1.3 \times 10^5 \text{ S/m} \), thickness = 45 \( \mu \text{m} \)
- Frequency Band: 2.4G ISM band, centered at 2.44 GHz.

Proximity feed Antenna

<table>
<thead>
<tr>
<th>( \varepsilon_r )</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.65</td>
<td>2.37 - 2.55 GHz = 180 MHz</td>
</tr>
<tr>
<td>1.7</td>
<td>2.34 - 2.52 GHz = 180 MHz</td>
</tr>
<tr>
<td>1.75</td>
<td>2.31 - 2.49 GHz = 180 MHz</td>
</tr>
</tbody>
</table>

Dimensions

- 53 x 53 x 0.15 x 4.0 mm\(^3\)
- 2.1 x 2.1 in\(^3\)

- Small Form Factor
  - 0.43 \( \lambda_0 \) x 0.43 \( \lambda_0 \) x 0.03 \( \lambda_0 \).
- A 7.32% impedance bandwidth.
- Gain: 5.7 dBi in the band of interest.
Linear Polarized Textile Antenna

Table I. COMPARISON BETWEEN LP TEXTILE ANTENNAS AND COTS ANTENNA

<table>
<thead>
<tr>
<th></th>
<th>Frequency (GHz)</th>
<th>Gain (dBi)</th>
<th>VSWR &lt; 2:1</th>
<th>Antenna Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>COTS</td>
<td>2.44</td>
<td>5 @ 2.4 GHz</td>
<td>200 MHz</td>
<td>3.3” x 3.3” x 0.3”</td>
</tr>
<tr>
<td>LP Textile Antenna</td>
<td>2.44</td>
<td>5.9 @ 2.44 GHz</td>
<td>180 MHz</td>
<td>2.1” x 2.1” x 0.15”</td>
</tr>
</tbody>
</table>

Radiation Efficiency greater than 83%
Linear Polarized Textile Antenna

---Comparison With Reference

**Antenna**

(a) Proposed Antenna

(b) Reference Antenna

S\textsubscript{11} response in Free-Space

S\textsubscript{11} response placed 2mm from a four layer rectangular tissue model
Linear Polarized Textile Antenna --- On-Body Performance

(a) $S_{11}$, (b) realized gain, and (c) radiation efficiency of the proposed proximity fed antenna with dielectric constant of 1.7 when mounted on different parts of the human body model.
Metasurface-enabled Circularly Polarized Textile Antennas

Material Properties (Textile - Jess Jur’s Group)
- Substrate: $\varepsilon_r = 1.65$
- Conductive Layer: $\sigma = 1.3 \times 10^5$ S/m, thickness = 45 μm
- Frequency Band: 2.4G ISM band, centered at 2.44 GHz.

Configuration of the circular-polarized (CP) textile metasurface antenna.

(a) Comparison of the CP bandwidth, maximum AR in band, and total thickness of the proposed antenna design for a dielectric constant of 1.7.

(b) Comparison of the CP bandwidth, maximum AR and maximum $S_{11}$ in band, of the proposed antenna design when the variation in the material’s permittivity is taken into account.
Metasurface-enabled Circularly Polarized Textile Antennas

Material Properties (Textile- Jess Jur’s Group)
Substrate: $\varepsilon_r = 1.65$  Conductive Layer: $\sigma = 1.3 \times 10^5$ S/m, thickness = 45 μm
Frequency Band: 2.4G ISM band, centered at 2.44 GHz.

Dimensions
88.08 x 101.85x 4.8 mm$^3$
3.5 x 4.0 x 0.19 in$^3$

The optimized dimensions are: $s = 23.3$, $ca = 5.6$, $lg = 17.28$, $wpx = 33.0$, $wp_y = 28.7$, $gx = 0.93$, $gy = 0.65$, $cd = 16.3$, all in mm.

<table>
<thead>
<tr>
<th>$\varepsilon_r$</th>
<th>CP Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.65</td>
<td>2.41 - 2.59 GHz = 180 MHz</td>
</tr>
<tr>
<td>1.7</td>
<td>2.39 - 2.57 GHz = 180 MHz</td>
</tr>
<tr>
<td>1.75</td>
<td>2.36 - 2.51 GHz = 150 MHz</td>
</tr>
</tbody>
</table>
Metasurface-enabled Circularly Polarized Textile Antennas

Circularly Polarized Textile Based Metasurface Antenna

Table II. COMPARISON BETWEEN CP TEXTILE ANTENNAS AND THE PRELIMINARY DESIGN RECENTLY DEVELOPED FOR ASSIST

<table>
<thead>
<tr>
<th></th>
<th>Frequency (GHz)</th>
<th>Thickness (λ)</th>
<th>Largest Dimension Footprint (λ)</th>
<th>CP BW (%)</th>
<th>Max Gain (dBiC)</th>
<th>Type of Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.3</td>
<td>0.046</td>
<td>0.67</td>
<td>3</td>
<td>--</td>
<td>Microstrip</td>
</tr>
<tr>
<td>2</td>
<td>1.625</td>
<td>0.016</td>
<td>0.35</td>
<td>1.7(^1)</td>
<td>7.5</td>
<td>Coaxial</td>
</tr>
<tr>
<td>3</td>
<td>2.45</td>
<td>0.098</td>
<td>0.62</td>
<td>23</td>
<td>3.5</td>
<td>CPW</td>
</tr>
<tr>
<td>4</td>
<td>1.635</td>
<td>0.025</td>
<td>0.9</td>
<td>2.5</td>
<td>5</td>
<td>Coaxial</td>
</tr>
<tr>
<td>CP Metasurface Design</td>
<td>2.44</td>
<td>0.039</td>
<td>0.83</td>
<td>7.2</td>
<td>6.7 (Realized Gain)</td>
<td>Microstrip</td>
</tr>
</tbody>
</table>

Compact Dual-Band Antenna Based on SIW Technology

Material Properties

Substrate: \( \varepsilon_r = 2.2 \) Rogers RO5880

Frequency Band: 2.4G ISM band, centered at 2.44 GHz.

The configuration of the proposed antenna. The dimensions are: \( L = 33 \), \( W = 43 \), \( h = 5.23 \), \( L_S = 27 \), \( W_S = 28.2 \), \( S_1 = 19.3 \), \( S_w = 2.3 \), \( L_Q = 20 \), \( W_Q = 37 \) all in millimeters.

Simulated \( S_{11} \) and Gain of the propose antenna.

Dimensions

33 x 43 x 5.23 mm\(^3\)
1.3 x 1.7 x 0.21 in\(^3\)

The radiation pattern at (a) 2.6 GHz and (b) 5.9 GHz.
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Future Work

Future work will include the manufacturing and characterization of both the proximity feed LP antenna and the CP-metasurface antenna using both rigid PCB and textiles materials (collaboration with Prof. Jess Jur’s group at NCsu).

We will also investigate the performance of the antennas taking into account the human body loading effects.

Incorporate the liquid metal material system into the SIW dual-band antenna design (collaboration with Prof. Michael Dickey at NCsu).
Outline

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Conclusion

- We have developed a compact textile based linearly polarized antenna which represents a key component for incorporation into the ASSIST SAP Testbed demo. The antenna possesses wide bandwidth and is extremely robust to structural deformations and human body loading effects. These properties make the antenna an ideal candidate for integration into a wearable garment.

- We have also designed a low-profile CP textile based metasurface antenna. The proposed antenna has robust performance taking into account the permittivity variation of the textile material, and wide CP bandwidth.

- We have started a collaboration with Prof. Jess Jur’s group at NCSU to develop garment-based wearable antennas that significantly outperform COTS antennas.
Publications

**Journal Papers**


**Books and Book Chapters**

Publications

- **Conference Papers**
Publications

- **Conference Papers (continued)**
Liquid Metals for Stretchable and Wearable Energy Harvesters

Taylor V. Neumann¹, Yasaman Sargolzaei va², Prof. Mehmet Ozturk², Prof. Michael Dickey¹
North Carolina State University
Chemical & Biomolecular Engineering¹
Electrical & Computer Engineering²
Typical (Rigid) Thermoelectric

Images from www
Using Inherently Soft Materials

Stretchable conductors have a trade-off between high conductivity and high stretchability. Liquid metal bypasses that limitation.
How to Pick a Liquid Metal?
Eutectic Gallium Indium (EGaIn)

- Low melting point (~15°C)
- Low viscosity
- Conductive
- Negligible vapor pressure
- Low toxicity

Source:
- Image courtesy Y. Lin

Manufacturing Process

1. Arrange TEG legs on substrate

2. Embed legs in PDMS

3. Connect legs by stenciling EGaIn

4. Encase interconnects in PDMS

5. Repeat process on bottom half

6. Encase bottom legs in PDMS

Bi$_{0.5}$Sb$_{1.5}$Te$_3$ p-type & Bi$_2$Se$_{0.3}$Te$_{0.5}$ n-type legs

Mechanical Testing
Testing the Device

Design Improvements
3D Printing EGaIn

Trlica, Parekh & Dickey et al., SPIE 2014
Spray Coating

Images from www

Well Diluted

Not Diluted Enough
Conformal Coatings
Co-Printing

Mechanical integrity is lacking and requires an encapsulation step.
Co-Printing

A rotating cradle of needles allow us to switch between materials, in this case liquid metal and a thermally curable polymer.
Impact of Improvements on Performance

3X improvement in performance with
- Thin PDMS encapsulation
- $\text{Al}_2\text{O}_3$ doped PDMS top/bottom layers
Benchmarking (w/o Air Flow)

<table>
<thead>
<tr>
<th>Output Power (µW/cm²)</th>
<th>Author/Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tamb = 15°C</td>
</tr>
<tr>
<td></td>
<td>Tamb = 22°C</td>
</tr>
<tr>
<td></td>
<td>Tamb = 1°C</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>S.E. Jo et al/25</td>
<td>PDMS + Dispensing printing of TE legs, Yonsei University (Korea)/2012</td>
</tr>
<tr>
<td>M.K. Kim et al/15</td>
<td>Flexible fabric+ Dispensing printing of TE legs, Yonsei University (Korea)/2014</td>
</tr>
<tr>
<td>S.J. Kim et al/15</td>
<td>CNT TE legs/ No encapsulation Texas A&amp;M University/2014</td>
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<td>S.E. Jo et al/20</td>
<td>PDMS + Dispensing printing of TE legs Yonsei University (Korea)/2015</td>
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<tr>
<td>Trung et al/15</td>
<td>Multi stage TEG/ PDMS+ Electrochemical deposition of TE legs/Tohoko University (Japan)/2017</td>
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<tr>
<td>Our work/22</td>
<td>ASSIST</td>
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</tbody>
</table>
Acknowledgements

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Yasaman Sargolzaeiav

Dr. Mehmet Ozturk
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Thank you!

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