NEXT GENERATION OF ORIGAMI-BASED TUNABLE RF STRUCTURES USING ADDITIVE MANUFACTURING
Outline

• Additive vs subtractive processes
• Motivation
• Origami-based Frequency Selective Surface (FSS)
• Origami-based Antenna “tree” Structures
• Conclusion
## Additive vs Subtractive Fabrication

<table>
<thead>
<tr>
<th>Technology</th>
<th>Feature size (µm)</th>
<th>Multi-layer</th>
<th>Cost</th>
<th>Speed</th>
<th>Waste</th>
<th>Printable area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milling</td>
<td>200</td>
<td>No</td>
<td>Low</td>
<td>Slow</td>
<td>High (Dust)</td>
<td>0.1</td>
</tr>
<tr>
<td>Laser Ablation</td>
<td>20</td>
<td>No</td>
<td>High</td>
<td>Slow</td>
<td>Medium (Vapors and dust)</td>
<td>0.05</td>
</tr>
<tr>
<td>Photolithography</td>
<td>0.01</td>
<td>Yes</td>
<td>High</td>
<td>Slow</td>
<td>High (Chemical)</td>
<td>0.66</td>
</tr>
<tr>
<td>Micro-contact Printing</td>
<td>0.1</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>Negligible</td>
<td>0.01</td>
</tr>
<tr>
<td>Gravure Printing</td>
<td>5-10</td>
<td>Yes</td>
<td>High</td>
<td>Fast</td>
<td>Medium (Excess ink)</td>
<td>∞</td>
</tr>
<tr>
<td>Screen Printing</td>
<td>10-20</td>
<td>Yes</td>
<td>Medium</td>
<td>Fast</td>
<td>Low (Excess ink)</td>
<td>0.8</td>
</tr>
<tr>
<td>Inkjet-printing</td>
<td>1-20</td>
<td>Yes</td>
<td>Low</td>
<td>Fast</td>
<td>Negligible</td>
<td>∞</td>
</tr>
</tbody>
</table>
Advantages of Fully printed systems

• Low-cost fully-printed systems
  – Removal of mounted discrete components
  – Stackable interconnects and crossovers
  – Higher levels of complexity and integration

• Ability to post-process onto CMOS (long term)
  – High gain antennas
  – Reduce chip area (post-processed inductors and capacitors)
  – Non-CMOS compatible components and sensors
Motivation

• Frequency Selective Surfaces (FSS)
  – Periodic array of resonating elements that filters out electromagnetic waves
  – Applications: radomes, stealth etc.
• Tunable FSS
  – Traditional approaches: lumped components, specialized substrates and MEMS-based systems
  – Disadvantages: limited tunability (15-20%), complicated design, limited flexibility and expensive
• Proposed solution: Inkjet-printed origami-based FSS on paper
Origami-based FSS

- **Origami**: Japanese art of paper-folding
  - Transforms a 2D sheet into a 3D structure

- **Miura-Ori fold**
  - Unit cell: Defined by two lengths ($l_1$ & $l_2$) and two angles ($\theta$ & $\alpha$)
  - Single axis of folding

- **Miura-FSS**
  - “Bridge-like” structures increase flexibility of conductive traces
Fabrication process

- Start with 110\(\mu m\) thick cellulose paper - use porosity
- Perforate Miura pattern on the paper
- Inkjet print dipole elements
  - 10 layers of SNP ink sintered for 1.5 hr.
- Fold the pattern manually
  - Folding can be automated by using heat sensitive materials or hydro-folding
Fabricated Miura-FSS

"bridge-like" structures

120°  90°  60°
Measurement setup

- 3D-printed frames are used to ensure uniform folding across the structure
- Effect of substrate thickness can be ignored
Continuous change is resonant frequency with folding
Results match very closely to theoretical values
Bandwidth increases (to 50%) with higher values of angle of incidence (Aoi)
High Aoi rejection due to 3D V-shaped elements in folded state
Motivation

• Reconfigurability
  – Frequency
  – Gain
  – Radiation pattern
  – Polarization

• Reconfigurable Antennas
  – Adapt to changing requirements
  – Add functionality
Reconfigurable Antennas

• Based on RF-MEMS
  – Drawbacks
    • Power handling
    • Flexibility
    • Cost

• Microfluidics and liquid metal
  – Stretchable
  – Flowable
    • Tune sizes/shapes
    • Enable switching
    • Change coupling


Reconfigurable Antennas

• Based on mechanical changes
  – Origami
    • Orientation
    • Radiation pattern

• Multiple antennas + switches
  – Interference
Operation principles

• Antenna “tree” platforms
  – Branch: antenna with matching (dielectric microfluidics channels)
  – Root: common feed
  – Blood: liquid metal alloy (LMA)
  – Trunk: origami scaffolding structures
Operation principles

- Origami scaffolding structure – trunk of the “trees”
- Zipper-tube based on Miura origami structure

3D-printing Fabrication

• Complex 3D structures
  – 3D antennas
  – Microfluidics channels
  – Origami scaffolding structures

• Stereolithography (SLA)
  – Printer: FormLabs Form 2
    • Spatial resolution: 50 μm

<https://www.engineersgarage.com/articles/3d-printing-processes-vat-photo-polymerization>
3D-printed Dielectric Material

- Flexible resin
  - 80% elongation
  - Characterization
3D-printed Origami

- No manually folding
- Easy to parameterize
- Good for prototype
- Voronoi Tessellation
  - Randomness to increase robustness
  - Reduce strain / enhance flexibility
  - Reduce dielectric loading & loss
  - Reduce material consumption by 73%

http://philogb.github.io/blog/2010/02/12/voronoi-tessellation/
Liquid Metal Allay (LMA)

- No failure point when folding
- Metallization of 3D printed objects
- EGaIn (75 wt % Gallium and 25 wt % Indium)
  - Conductivity: 3.4483e6 S*m (1/17 of bulk copper)
  - Flexible/stretchable
    - Melting point: 15.5°C
  - Flowable
    - Viscosity: 1.9910 mPa*s (2x of water, 1/4000 of ketchup)
  - Non-toxic
  - Controlled by microfluidics
  - NaOH to avoid oxidation skin

<https://www.youtube.com/watch?v=jow4ldr6HNs>
Antenna on “trees”

• Helical antenna
  – Circular polarization @ 3 GHz
• Zigzag antenna
  – Linear polarization @ 5 GHz
• Origami
  – Radiation pattern $HPBW \propto \frac{1}{\sqrt{l}}$
Zig-zag antenna on the “tree”

- Return loss
  - Frequency relatively stable: < 2% shift

![Graph showing return loss with frequency on the x-axis and S11 in dB on the y-axis. The graph includes several lines representing different simulations and measurements with annotations indicating changes in size from 22 mm to 51.6 mm and 70.5 mm.](image)
Zig-zag antenna on the “tree”

- Radiation pattern
  - HPBW: $28^\circ \rightarrow 60^\circ$ (compressed)
  - Maximum gain direction: $175^\circ \rightarrow 150^\circ$ (compressed)
Helical antenna on the “tree”

- Return loss
  - Frequency relatively stable
Helical antenna on the “tree”

- Radiation pattern
  - HPBW $60^\circ \rightarrow 90^\circ$ (compressed)
Conclusions

- Alternate approach to realize tunable FSS using origami-based structures on paper substrate
- Special “bridge-like” structures increases the flexibility of the conductive traces
- Miura-FSS facilitate continuous range of frequency and bandwidth tunability
- First-of-its-kind reconfigurable antenna “tree”:
  - A novel approach to realize integrated reconfigurable antennas
    - LMA
    - Microfluidics
    - Origami
    - Voronoi
  - Flexible 3D printing
  - Broad range of compression/elongation ratios
  - Proof-of-concept antenna “tree” prototype with zigzag and helical antennas
References


Acknowledgement
Thank you