Conformal and Spectrally Agile Ultra Wideband Phased Array Antenna for Communication and Sensing

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Outline

State of the Practice & State of the Art

UWB TCDA Concept and Implementation

Digital Beamforming Concept and Implementation

UWB Phased Array Applications
<table>
<thead>
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<th>Benefits</th>
<th>Limitations</th>
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<tr>
<td>Graceful degradation</td>
<td>Narrowband/fixed frequency operation</td>
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<tr>
<td>Mechanical simplicity</td>
<td>Broad beams (few elements)</td>
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<tr>
<td>Multi-function</td>
<td>Low efficiency (10-35%)</td>
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<tr>
<td>Agile</td>
<td>Single Access</td>
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<tr>
<td>Conformal</td>
<td>High cost</td>
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<td>Size, Weight</td>
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<td><strong>Examples of SoP Phased Arrays for Space Applications</strong></td>
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<td>--------------------------------------------------------</td>
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<tr>
<td><strong>MESSENGER</strong></td>
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<tr>
<td>• 2 X-band arrays on board</td>
<td></td>
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<tr>
<td>• 208 slot elements</td>
<td></td>
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<tr>
<td>• 1-D scanning to 45°, 4-bit phase shifters</td>
<td></td>
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<tr>
<td>• 11W RF output, 35% efficiency</td>
<td></td>
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<td>• 4.88kg</td>
<td></td>
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<tr>
<td><strong>EO-1</strong></td>
<td></td>
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<tr>
<td>• 64-element X-band array on board</td>
<td></td>
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<tr>
<td>• 2-D scanning to 60° (4 dB loss)</td>
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<tr>
<td>• 5W RF output, 11% efficiency</td>
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<tr>
<td>• 105 Mbps link</td>
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<tr>
<td><strong>TDRSS</strong></td>
<td></td>
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<tr>
<td>• 30-element S-band, nonuniform array</td>
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<tr>
<td>• 12° scanning</td>
<td></td>
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<tr>
<td><strong>BRAIN (SLS)</strong></td>
<td></td>
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<tr>
<td>• S-band, very little known</td>
<td></td>
</tr>
<tr>
<td><strong>ORION</strong></td>
<td></td>
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<tr>
<td>• 13 patch array, S-band</td>
<td></td>
</tr>
</tbody>
</table>

(Top View of Spacecraft)
## State of the Art - Trade Off Tables

<table>
<thead>
<tr>
<th>Greater Bandwidth, Scan Angle</th>
<th>( P_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater Electrical Thickness</td>
<td>( k_0 h )</td>
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</tbody>
</table>

**Vivaldi**
(Balanced Antipodal Vivaldi Array)

**TCDA**
(Tightly Coupled Dipole Array)

**BAVA**
(Balanced Antipodal Vivaldi Array)
Expanded Comparisons

**Efficiency**
- 0%: EO-1
- 100%: MESSENGER

**Bandwidth**
- 10%: EO-1
- 10:1: Patch, BAVA, Vivaldi, TCDA

**Scanning**
- 10°: TDRSS, Patch, Vivaldi, BAVA, MESSENGER, EO-1, TCDA

**Data Capacity**
- 10Mbps: TDRSS, MESSENGER, EO-1
- >1Gbps: HIMSS, BAVA, TCDA
Arrays for Commercial Timescales seeks versatile array components for S-X band

- Heavily based on analog reconfiguration
- Goals and technology limited to lower frequencies
- No backend integration
- Generally high cost

Benefit/Novelty of our approach:

- Scalable in frequency and size
- Full system integration
- Software-defined operation
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Frequencies of Interest

- Need for integration of multiple functions to reduce SWaP
- Need access to high data-rate comms and high resolution imaging, across fragmented spectrum
- Should be low cost
Tightly Coupled Dipole Arrays (TCDAs) utilize capacitive coupling between elements to support low frequencies across multiple elements.

[1] Munk’s Current Sheet Array (CSA) introduces inter-digital capacitors to achieve 4:1 BW

[2] Doane adds integrated balun to demonstrate TCDAs with >7:1 BW and $\lambda_{\text{low}}/14$ profile
Expanded Background

[3] Moulder designs loaded TCDA with >10:1 bandwidth and <λ_{low}/18 profile; 14:1 infinite array bandwidth (some loss)

[4] Dual-polarized, lossless TCDA demonstrated with 6:1 BW while scanning to ±60°; 8:1 at broadside

However...

All previous work at <5GHz
Must extend operation to Ku, Ka, and mm-Wave bands
  • Fabrication limitations
  • Cannot be simply scaled

18GHz Proof of Concept

3-layer PCB
8 mil (200um)
feature size
- Can be scaled to higher frequencies

3.5-18.5 GHz
VSWR < 2 (Broadside)
VSWR < 2.6 (scan)

Linear taper to 50 ohm (dashed) approaches nominal 90 ohm (solid) performance

VSWR<2.2 at 70° E-plane
4-17.25GHz (88% of Broadside BW)
What About Even Higher Frequencies?

**Previous Works**

- **0.5-4 GHz**
  - 4 mil feature size

**Ku-TCDA**

- At 18 GHz, nowhere near the limit for PCB fabrication!

**Ka and Millimeter Wave**

- With minimal alteration, this design can scale to Ka and above
  - **3.5-18.5 GHz**
    - 8 mil features
  - **7-37 GHz**
    - 4 mil
  - **9-49 GHz**
    - 3 mil
    - (State of Practice)
  - 3.75 mm (State of Practice)

Array and feeding network are fabricated on Printed Circuit Board (PCB) which can support down to 3 mil (~75um) features.

Groundplane and superstrate are CNC milled.
Scaled Arrays with Real Materials

7–37 GHz Matching

- Broadside
- 45° E-Plane
- 45° H-Plane

9–49 GHz Matching

- Broadside
- 45° E-Plane
- 45° H-Plane

Up to 40 GHz available

Layer Stacks:

- 18 GHz
  - 5 mil Duroid 5880 ($\varepsilon_r=2.2$)
  - 4 mil Polyflon Polyguide ($\varepsilon_r=2.32$)
  - 5 mil Duroid 5880 ($\varepsilon_r=2.2$)

- 37 GHz
  - 5 mil Duroid 5880 ($\varepsilon_r=2.2$)
  - 2 mil Polyflon Polyguide ($\varepsilon_r=2.32$)
  - 5 mil Duroid 5880 ($\varepsilon_r=2.2$)

- 49 GHz
  - 4 mil CuFlon ($\varepsilon_r=2.1$)
  - 2 mil Polyflon Polyguide ($\varepsilon_r=2.32$)
  - 4 mil CuFlon ($\varepsilon_r=2.1$)

3–50 GHz Coverage

Novak, Miranda, Volakis, "Ultra-Wideband Phased Array Antennas for Satellite Communications up to Ku- and Ka-Band", IN SUBMISSION

ElectroScience Laboratory
Ku Array Fabrication in PCB

- Four-layer PCB
- Rogers Duroid 5880
- 14mil total

SMP ports
- Push-to-connect
- 4mm wide

- All elements identical
- Low-cost fabrication
- Fabrication easily scaled
- Frequency scalable
Measurement Setup

NASA GRC Far-Field Range

64 element array with extended groundplane

Scan Patterns: 8.4 GHz, 13GHz, 17.5GHz

Ka to mm-Wave Concept

Nominal band: 24-86GHz
\( \lambda_{hi} = 3.49\text{mm} (~140\text{mil}) \)

- Using Low-Temperature Co-Fired Ceramic (LTCC) or Multilayer Organic laminates (MLO)
- Requires planar or extremely simplified balun for all-in-one fabrication
- Additional matching stages can be inserted below groundplane

Non-optimized broadside VSWR
- Not interested in matching as much as resonance-free band
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Current SoA Beamformers

Analog Beamformer
- Well understood
- Single Access
- Many phase shifters
  - Expensive
  - Inefficient
- Narrowband

Digital Beamformer
- Multiple Access
- High efficiency
- Many ADC
  - Power Hungry
  - Large area
- Heavy FPGA requirements
New Digital Beamforming Concept

On-Site Coding Digital Beamformer

- Single ADC serves multiple elements
- Orthogonal codes preserve individual element signals
- Multiple Access
- High efficiency
- Reduced ADC and FPGA
- Broadband
Utilizing on-site coding in analog signal path, we realize hardware-reduced digital beamforming:

- Up to 10x reduction in ADCs
- Wideband, multiple beam operation
- Fast scanning
- Software-defined operation

• 4-channel system has been demonstrated at 2GHz
• Demonstration up to 12GHz being prepared
Digital Beamforming up to 10 GHz

- Columns of 8 elements routed to power combiners
- 4 channels routed, maximum 3 measured due to equipment malfunction
- Demonstrate azimuthal scanning in H-Plane
- Demonstrate Direction-of-Arrival estimation from 2 channels
- Receive and process separate signals at 6 and 10 GHz
- Beam patterns being compared against previous measurements

Measurements conducted 9/14 and 9/15, results being processed.
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Smart Relays

Reduce end-to-end link burden

Software-Defined Radio

- Spectral agility
- Future-proof
- Coding & waveform flexibility
- Multi-Gbps link capability

Planetary Exploration

SmallSat/CubeSat

- Low cost exploration
- Potentially distributed architecture for communication and sensing

Summary

- We have an ultra-wideband antenna which is:
  - Low cost, low profile, low weight
  - Scalable in size and frequency
- Paired with novel digital beamforming architecture
  - Multiple access and simultaneous multi-beam scanning
  - Up to 10x reduction in ADC count (thus power and size)
- Both fabricated and measured

Future Work

- Fabricate and measure 20-80 GHz array
- Build an integrated, RF–digital, mm-Wave phased array
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