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
### Benefits
- Graceful degradation
- Mechanical simplicity
- Multi-function
- Agile
- Conformal
- Size, Weight

### Limitations
- Narrowband/fixed frequency operation
- Broad beams (few elements)
- Low efficiency (10-35%)
- Single Access
- High cost
Examples of SoP Phased Arrays for Space Applications

**MESSENGER**
- 2 X-band arrays on board
- 208 slot elements
- 1-D scanning to 45°, 4-bit phase shifters
- 11W RF output, 35% efficiency
- 4.88kg

**EO-1**
- 64-element X-band array on board
- 2-D scanning to 60° (4 dB loss)
- 5W RF output, 11% efficiency
- 105 Mbps link

**TDRSS**
- 30-element S-band, nonuniform array
- 12° scanning

**BRAIN (SLS)**
- S-band, very little known

**ORION**
- 13 patch array, S-band
State of the Art - Trade Off Tables

<table>
<thead>
<tr>
<th>TCDA</th>
<th>Vivaldi</th>
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<tbody>
<tr>
<td>(Tightly Coupled Dipole Array)</td>
<td>(Balanced Antipodal Vivaldi Array)</td>
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- **Greater Bandwidth**
- **Scan Angle**
- **Greater Electrical Thickness**
Expanded Comparisons

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

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

**Scanning**
- 10°: TDRSS
- 60°: Patch, Vivaldi, BAVA

**Data Capacity**
- 10Mbps: TDRSS
- >1Gbps: MESSENGER, EO-1
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.

Circuit Model

[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**

- **3.5-18.5 GHz**
  - 8 mil features

**Ka and Millimeter Wave**

- **7-37 GHz**
  - 4 mil

- **9-49 GHz**
  - 3 mil
  - (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.

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

With minimal alteration this design can scale to Ka and above.
Scaled Arrays with Real Materials

Layer Stacks:

18 GHz
- 4 mil Polyflon Polyguide (ε_r=2.32)
- 5 mil Duroid 5880 (ε_r=2.2)

37 GHz
- 2 mil Polyflon Polyguide (ε_r=2.32)
- 5 mil Duroid 5880 (ε_r=2.2)

49 GHz
- 4 mil CuFlon (ε_r=2.1)
- 2 mil Polyflon Polyguide (ε_r=2.32)
- 4 mil CuFlon (ε_r=2.1)

Frequency (GHz)
- 7--37 GHz Matching
  - VSWR
  - Broadside
  - 45° E-Plane
  - 45° H-Plane

- 9--49 GHz Matching
  - VSWR
  - Broadside
  - 45° E-Plane
  - 45° H-Plane

- 3--50 GHz Coverage
  - VSWR
  - Frequency (GHz)

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

Measured Broadside Gain

Co-pol
Cp-pol
Theory
Scan Patterns: 8.4 GHz, 13GHz, 17.5GHz

Details in upcoming "Wideband Array for C, X, and Ku-Band Applications" IEEE APS 2015
Ka to mm-Wave Concept

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

- 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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UWB Phased Array Applications

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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