Electronically-Steerable Antennas for Millimeter-Wave Frequency Range

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Motivation

Electronically steerable antennas are integral to most millimeter-wave radio systems.

Steerable antennas are employed or envisioned for:
- Automotive radar
- Navigation and landing aids
- LEO satellites
- On the move SATCOM
- Cellular communication infrastructure
- Space systems
- Short range ultra high speed data communication
- WLAN
Different Approaches To Beam Steering

Common methods for beam steering include:

- Mechanical steering
- Phased arrays (active and passive)
- Multi-beam quasi-optical systems (passive)
- Scanned quasi-optical system (active and passive)
- Frequency-scanned leaky-wave antennas (passive)
- Electronically-scanned leaky-wave antennas (passive)
- Digital beam-forming (active)
Comparison Between Active and Passive Methods

<table>
<thead>
<tr>
<th></th>
<th>Active</th>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Low</td>
<td>Low-High</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Small-Medium</td>
<td>Small-Large</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Low-Medium</td>
<td>Low-High</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>Low</td>
<td>Hi</td>
</tr>
<tr>
<td><strong>Gain/Efficiency</strong></td>
<td>High</td>
<td>Low-Medium</td>
</tr>
<tr>
<td><strong>Power handling</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Low</td>
<td>Low-High</td>
</tr>
<tr>
<td><strong>DC Power consumption</strong></td>
<td>High</td>
<td>Low-Medium</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>Poor</td>
<td>Good</td>
</tr>
</tbody>
</table>
MEMS phase shifters and monolithic phased-arrays:

- Topalli et al., 2008
- Lakshminarayanan et al., 2006
- Hung et al., 2004

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State of the Art in IC Phase-Shifters

Passive 3-Bit Delay Line in 65 nm CMOS

Active 4-Bit in 0.18 um BiCMOS

Koh et al., 2008

Yu et al., 2008

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Space-Fed Arrays vs. Phased Arrays With Constrained Feed Networks

- At millimeter-wave frequencies (MMW) larger arrays are often implemented in the form of space-fed arrays (lens-arrays or reflectarrays).
- Space-feeding eliminates the loss and parasitic radiations of the feed network.
- Beam-steering in the case of reflectarrays and lens-arrays can be achieved by integrating phase-control devices with the array elements.
Multi-Beam Lens-Array and Reflectarray Examples

K-band discrete lens array with patches and delay lines.

58 GHz 3-beam folded reflectarray

Romisch et al., 2003

Thiel and Menzel, 2006
Multi-Beam 2D Lens-Array Examples

Modified Rotman Lens

2D Lunberg Lens

Schulwitz et al., 2008

Kenichi, 2002
Scanned Lens-Array Examples

- **Lockheed Martin/ Radant Lens-Array**
  - Maciel et al., 2007
  - 25,000 switches, 0.4 m², X band

- **Teledyne Scientific Lens-Array uses waveguide phase-shifters with Schottky diode electromagnetic crystal tuners (EMXT) side walls.**
  - Xin et al., 2005
  - EMXT Sidewalls
  - Bias controls
Scanned Reflectarray Examples

X-band reflectarray based on waveguide reflective 2-bit phase-shifters. Uses PIN diode-enabled switchable printed circuit loads.

60 GHz reflectarray based on pin-diode-loaded patch antennas with 1-bit phase shift.

Apert et al., 2006 (Thales)

Kamoda et al., 2009 (NHK, Japan)
Ideas Proposed for Monolithic MEMS Lens-Arrays and Reflectarrays

- Almost all of the viable topologies are for reflectarrays:

  Perruisseau-Carrier et al., 2008

  Bayraktar et al., 2008

  Sorrentino, 2008

  Schaffner et al., 2001
Leaky Wave Antenna Examples

**Frequency-Scanned LWA Based on Composite Transmission Feed-Line**

Caloz & Itoh, 2004

**Electronically-Scanned LWA Based on Loaded Composite Feed-line**

Lim et al., 2004
Hybrid vs. Monolithic Integration

• In hybrid implementation, MEMS phase-shifters, switches, or tuning elements are fabricated and packaged separately and are assembled into the array topology.
  - Requires post assembly and hence is more tedious fabrication.
  - The large size of the packaged devices limits the minimum cell size, scan performance, and frequency range.
  - Assembly errors and package parasitics can seriously impair performance at millimeter-wave frequencies.
  - Is feasible even in the absence of a high yield MEMS process

• In the monolithic implementation, MEMS devices are fabricated on the same substrate as the antennas and the rest of the RF structure. The devices can be packaged individually using dielectric dome or in wafer level.
  - Advantages include compact design, potential for high density integration, and high frequency operation.
Difficulties of Monolithic Integration

- Monolithic implementation is subject to a number of challenges:
  - Limits on the choice of substrate affecting the size of phase shifters and antenna performance
  - Increased mutual coupling through closely spaced unshielded phase-shifter circuits
  - RF coupling to the bias network
  - Parasitic radiations from phase-shifters and bias lines
  - Limit on the maximum size of the array
  - Need for a high-yield process with good uniformity across the wafer

- Most of the above problems can be overcome with creative topologies and careful design. The yield problem is a manufacturing issue that needs to be addressed by industry.
- Currently, efforts are under way to develop a high-yield MEMS foundry process that will hopefully address the yield issue.
Why Simple Phase-Shifter-Based Configurations Do Not Work Too Well?

- Wideband antennas in conjunction with matched delay lines or phase-shifters can be used to design wideband lens-arrays and reflectarrays.

- Simulated phase for an element with 100% bandwidth for $\phi = [0:22.5:337.5]$:

\[ \begin{align*}
\text{Simulated phase graph} & \quad \begin{cases}
\text{Phase} & \quad \text{GHz}
\end{cases}
\end{align*} \]
Why Simple Phase-Shifter-Based Configurations Do Not Work Too Well?

- Now assume a more practical value the antenna bandwidth 10%:
Arrays Using Antenna-Filter-Antenna Elements

- To overcome the unwanted changes in the frequency response, the antennas and phase-shifters must be designed together.
- The antenna and phase-control circuitry can be combined to form a bandpass filter. We give these composite elements the name Antenna-Filter-Antennas or AFA.
- AFA’s are usually three-layer structures that are composed of two antennas and a number of microwave resonators.
- For resonant antennas, the reactive part of the antenna impedance is absorbed in the structure of the filter.
Example of absorbing antenna reactance in the filter design for the case of slot antennas:

![Diagram showing the elements of a bandpass filter and slot antennas in both receive and transmit modes.](image)
Fixed AFA Examples Using Microstrip and Slot Antennas

\[ E_{\text{inc}} \rightarrow \begin{array}{l}
\bar{E}_{\text{inc}} \quad \text{CPW Resonator} \\
\end{array} \]

- $\varepsilon_r = 4.6, h = 500 \mu m$
- $\varepsilon_r = 4.6, h = 500 \mu m$

- $\sigma \approx 3.8 \times 10^7 \text{ S/m}$
- $t \approx 3 \mu m$

- $\sigma \approx 5 \times 10^7 \text{ S/m}$
- $t \approx 18 \mu m$

\[ E_{\text{inc}} \uparrow \begin{array}{l}
\bar{E}_{\text{inc}} \quad \text{SL Resonator} \\
\end{array} \]

- $\varepsilon_r = 2.2, h = 375 \mu m$
- $\varepsilon_r = 2.2, h = 375 \mu m$

Graphs showing measured, circuit simulation, and HFSS results for transmission coefficients $S_21$ and $S_11$.
Reconfigurable AFA’s as Phase-Shifting Devices

- If their frequency response could be made tunable, AFA’s can be used as phase-shifting elements to form lens-arrays or reflectarrays.

- A more practical approach is to design reconfigurable AFA elements that can jump between different order bandpass modes.
Focal Plane Scanning Using Fixed Lens-Arrays (Tuned Elements)

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Focal Plane Scanning Using Fixed Lens-Arrays (Multi-Moded Elements)

E-Plane Scanning

H-Plane Scanning

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A two-bit reconfigurable AFA can be derived from the slot-based fixed design.
Result for Lens-Array with Compact AFA Elements

Measured frequency response under oblique incidence

Radiation Patterns for the boresight and beam scanned to 30° and 60° in the E-plane

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The MEMS implementation is based on cantilever DC contact switches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [μm]</td>
<td>125</td>
<td>Actuation area [μm^2]</td>
<td>70 x 80</td>
</tr>
<tr>
<td>Width [μm]</td>
<td>80</td>
<td>Actuation voltage [V]</td>
<td>44</td>
</tr>
<tr>
<td>Height [μm]</td>
<td>1.7</td>
<td>Switch resistance [Ω]</td>
<td>0.4–0.8</td>
</tr>
<tr>
<td>Membrane layer</td>
<td>Gold</td>
<td>C_u [F]</td>
<td>25</td>
</tr>
<tr>
<td>Thickness [μm]</td>
<td>3.5</td>
<td>Isolation [dB]</td>
<td>-20 (10GHz)</td>
</tr>
<tr>
<td>Spring constant [N/m]</td>
<td>30</td>
<td>Isolation [dB]</td>
<td>-10 (20GHz)</td>
</tr>
<tr>
<td>Sacrificial layer</td>
<td>PMMA</td>
<td>Loss [dB]</td>
<td>&lt; -0.3 dB</td>
</tr>
</tbody>
</table>

Topology:
MEMS Implementation Challenges

- Switch and structural imperfections:
  - Switch resistance
  - Switch upstate capacitance
  - Bias Lines
  - Air gap between substrates
  - SU-8 loss

- Lack of standard foundry process
- Yield
- Low-temperature packaging
- Long term reliability
Fabrication Process

1. 3000 Å-thick sputtered SiCr (For high resistivity)
2. 4000 Å-thick PECVD oxide

Bias lines and insulator

3. 200/2000 Å evaporated Ti/Au and 1.5 μm-thick plated Au
4. In the back side, cover a layer of photoresist

Slot antenna

5. RIE PECVD oxide.
6. 200/6000 Å sputtered Ti/Au

Contact sites of switches

7. 1.4 μm-thick PMMA
8. 3000 Å-deep RIE etched dimple

Sacrificial layer and dimple

9. 80/1600 Å sputtered Ti/Au and 3.5 μm-thick plated Au beam

Cantilever

10. Wafer bonded and connect to PCB through Al wire bonds.

Slot antenna and adhesion layer
The advantages of using SU–8:
• High aspect ratio (Microchem 2025)
• Low bonding temperature (~50 °C)
• Low loss ($\varepsilon_r = 3.8$, $\tan\delta = 0.02$)
• High bonding strength

The disadvantage of using SU–8:
• Non–hermetic packaging
• Highly sensitive to bonding temperature
Test Structure and Measurement Setup

- Modal Frequency response can be measured using a quasi-optical Gaussian beam measurements setup composed of two printed focusing arrays and a network analyzer.
- The small size of the focal spot (~2 cm) allows for measuring the frequency response in small zones across the array.
Localized Measurement of the Modal Frequency Response

- Measured and curve-fitted S-parameter of region2 for amplitude and phase (simulations are for $R_s = 6-9 \, \Omega$).
Measured Scanning Performance

- Effective scan range: $\pm 40^\circ$
Yield and Gain Analysis

- Curve fitting results in an average of 6-9 Ω for switch resistance.
- The high resistance can be caused by:
  - Low contact force due to switch curl up
  - Organic contaminants at the contact sites
  - Low percentage of working switches (~40-50%)

**MPLA Gain and Loss Analysis**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Size</td>
<td>7.76 cm²</td>
</tr>
<tr>
<td>Ideal Directivity</td>
<td>21 dBi</td>
</tr>
<tr>
<td>AFA Insertion Loss (average)</td>
<td>8.0 dB</td>
</tr>
<tr>
<td>Quantization Phase Error Loss</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Cylindrical Phase Error Loss</td>
<td>0.7 dB</td>
</tr>
<tr>
<td>Aperture Taper Loss</td>
<td>2 dB</td>
</tr>
<tr>
<td>Other Unidentified Losses</td>
<td>0.6 dB</td>
</tr>
<tr>
<td>Measured Gain</td>
<td>9.2 dB</td>
</tr>
</tbody>
</table>

**Inherent Losses**

- AFA Insertion Loss (average) 8.0 dB
- Quantization Phase Error Loss 0.5 dB
- Cylindrical Phase Error Loss 0.7 dB
- Aperture Taper Loss 2 dB
- Other Unidentified Losses 0.6 dB
- Measured Gain 9.2 dB
Reflectarray Topology and Its Advantages

- In lens-array is that biasing individual elements is basically impossible.

- This problem is solved in reflectarrays, where elements can be easily accessed from back-side without the bias network causing blockage or parasitic radiations.
A reflective AFA topology can be obtained from the transmittive design:
Two-Bit Transmittive AFA Element: Operation

Operation in Bandpass Modes

Polarization Rotation Action

Incident wave | Desired reflection | Undesired reflection
--- | --- | ---
\[ \uparrow \] | \[ \uparrow \] | \[ \uparrow \]
\[ \uparrow \] | \[ \uparrow \] | \[ \uparrow \]
\[ \uparrow \] | \[ \uparrow \] | \[ \uparrow \]
\[ \uparrow \] | \[ \uparrow \] | \[ \uparrow \]
Measured Response Using Proof of Concept Fixed Prototypes

- Measurement using one-port Gaussian beam setup:

\[
\Gamma_{co} = \frac{1}{2} \left( S_{11,(+45)} + S_{11,(-45)} \right) \quad \Gamma_{cr} = \frac{1}{2} \left( S_{11,(+45)} - S_{11,(-45)} \right)
\]
Reflectarrays can be fed in offset-fed and folded center-fed configurations.

Fixed reflectarrays were fabricated for these feed configurations and scan angles of 0, 15, 30, 45, and 60 deg.
Scanning Performance for the Offset-Fed Reflectarray

H-plane

- Meas
- Sim
- X-pol

(a) Gain (dB) vs Angle (deg)
- G: 13.9
- L: 13.7
- X: 14.7

(b) Gain (dB) vs Angle (deg)
- G: 13.9
- L: 13.3
- X: 18.2

(c) Gain (dB) vs Angle (deg)
- G: 13.0
- L: 12.1
- X: 14.3

(d) Gain (dB) vs Angle (deg)
- G: 11.6
- L: 11.2
- X: 16.9

(e) Gain (dB) vs Angle (deg)
- G: 8.2
- L: n.a
- X: 10.3

OEWG E: Measured E-plane pattern of OEWG

E-plane

- Meas
- Sim
- X-pol

(a) Gain (dB) vs Angle (deg)
- G: 14.2
- L: 13.1
- X: 11.2

(b) Gain (dB) vs Angle (deg)
- G: 14.1
- L: 13.7
- X: 12.8

(c) Gain (dB) vs Angle (deg)
- G: 12.4
- L: 14.3
- X: 13.5

(d) Gain (dB) vs Angle (deg)
- G: 11.2
- L: 12.7
- X: 14.7

OEWG H: Measured H-plane pattern of OEWG
Scanning Performance for the Folded Center-Fed Reflectarray

H-plane

(a) Meas: G: 14.8, L: 11.2, X: 15.2
(b) Sim: G: 15.0, L: 11.5, X: 14.7
(c) Meas: G: 14.6, L: 11.5, X: 15.0
(d) Sim: G: 13.6, L: 9.3, X: 14.1
(e) Meas: G: 13.5, L: 8.1, X: 11.5
(f) Sim: G: 13.0, L: 6.8, X: 15.5

E-plane

(a) Meas: G: 15.0, L: 12.1, X: 23.0
(b) Sim: G: 15.0, L: 13.0, X: 26.1
(d) Sim: G: 13.9, L: 13.7, X: 22.5

OEWG E*: Measured E-plane pattern of OEWG
OEWG H*: Measured H-plane pattern of OEWG
(From the backside of reflectarray)
A large part of the loss is due to the feed spillover.

Spillover loss can be improved by synthesizing the pattern of the feed antenna, for example by embedding a lens-array in the feed window in the folded center-fed array.

Experiments show that even a very small lens can improve the efficiency by 1 dB compared to a simple open-ended waveguide feed.
Conclusion

- Space-fed and 2D quasi-optical arrays are best suited to medium to large MMW steerable antenna applications.
- Successful implementation of lens-arrays and reflectarrays requires a high degree of control over frequency response.
- Especially in monolithic designs, this requires that antennas and phase-control devices are designed and optimized together. AFA’s offer an example of such designs.
- Reconfigurable lens-arrays and reflectarrays can be realized using multi-bit AFA’s. The quantization phase error has a small impact on aperture efficiency or sidelobe level due to space feeding. Careful design can minimize the effect of parasitic radiations. The performance of these devices, hence, is basically limited by the quality of fabrication.
- 2D lens devices can also be implemented in miniature dimensions and used as low-loss beam-forming networks. They can be combined with MEMS or CMOS switches to form simple and low-cost beam-steering solutions at millimeter-wave frequencies.
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