Broadband Slow-Wave Phase Shifters Based on Thin Ferroelectric Films for Reflectarray Antennas

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We have developed relatively broadband K- and Ka-band phase shifters using synthetic (slow-wave) transmission lines employing coupled microstripline "varactors". The tunable coupled microstripline circuits are based on laser ablated BaSrTiO films on lanthanum aluminate substrates. A model and design criteria for these novel circuits will be presented, along with measured performance including anomalous phase delay characteristics. The critical role of phase shifter loss and transient response in reflectarray antennas will be emphasized.
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Outline

• Phased Array Antennas
  • Reflectarray Antenna Technology and Applications
  • Reflectarray Antenna Based On Thin Ferroelectric Film Phase Shifters
• Effect of Phase Shifter Insertion Loss on Reflectarray Performance
  • Efficiency
  • Sensitivity
• Effect of Phase Shifter Insertion Phase Characteristics on Reflectarray Performance
  • Impact of transient during beam evolution
  • Modulo $2\pi$ effect on intersymbol interference and bit error rate
• Ferroelectric Film Phase Shifters
  • Slow Wave Phase Shifters
  • Negative Group Delay
  • The Ultimate Phase Shifter?
Direct Radiating Phased Array vs. Passive Reflectarray vs. Scanning Reflectarray

Raytheon 0.2 m Space Qualified K-Band Scanning MMIC Phased Array

JPL 0.5 m Fixed Beam Ka-Band Reflectarray

X-Band ~1m Scanning Ferroelectric Reflectarray

Gain: 29 dB (Limited)
Watts Consumed/dB EIRP: 7.2

Gain: 42 dB (Scalable)
Watts Consumed/dB: N/A

Gain: 32 dB (Scalable)
Watts Consumed/dB EIRP: 0.95

GaAs MMIC Phase Shifters

Rotated Patch Elements

Thin Film Ferroelectric Coupled Line Phase Shifters
What is a Reflectarray?

Technology Description:
- A scanning reflectarray consists of a flat surface with diameter $D$ containing $N$ integrated phase shifters and $N$ patch radiators that is illuminated by a single feed at a virtual focus located a distance $f$ from the surface such that $f/D \approx 1$. The modulated signal from the feed passes through the $N$ reflect-mode phase shifters and is re-radiated as a focused beam in essentially any preferred direction in the hemisphere in front of the antenna, as in a conventional phased array.
- Enabled by low loss ferroelectric phase shifters
- Simple device lithography – smallest feature size is $\approx 10 \mu m$ compared to sub-micron for MMIC devices
- Simple construction technique – no RF feedthroughs, only three layers, one dc bias connection per phase shifter compared to at least five for an MMIC phase shifters
- No beam forming manifold therefore arbitrarily high gain

Potential benefits
- 10 X to 100 X cost reduction compared to direct radiating phased array
- Aperture size can be arbitrarily large therefore gain is not limited as in a conventional MMIC phased array (EIRP derived from aperture, not amplifiers)
- Enabling for high EIRP space applications since cooling is not an issue
- In the case of a transmit array, efficiency is intermediate between a MMIC array and a gimbaled parabolic reflector. About a 5 X reduction in power relative to GaAs MMIC based array for high EIRP
- High reliability compared to a gimbaled reflector – no moving parts
208 Element Passive Reflectarray E-Field Pattern
(Vertical Polarization)

Passive Array - Vertical Scatter Pattern

Magnitude (dB)

Theta (degrees)

-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40

0 -5 -10 -15 -20 -25 -30 -35 -40

18.9 GHz

Copper Side

Patch Side
128 Element Passive Reflectarray E-Field Pattern
(Horizontal Polarization)

Passive Array - Horizontal Scatter Pattern

18.9 GHz

Magnitude (dB)

 Theta (degrees)
Steerable Reflectarray Applications @ 32 GHz

- e.g. Rover to MSO Relay Satellite with 1 meter receive aperture
- Single 34 meter DSN antenna
- Also, feed for inflatable to provide several beamwidths steering
Calculated pointing loss as a function of pointing error at X- and Ka-band for 5 and 10 meter antenna assuming a circular aperture and an 11 dB edge taper.
TWT power diminishes with element count but eventually offset by ISI loss.
Reflectarray cost dominated by ferroelectric materials cost.
TWT cost assumed proportional to output power.
Aperture Gain and Power Consumption Advantage of a Ferroelectric Reflectarray Antenna Compared to a Conventional Direct Radiating MMIC Phased Array at 26 GHz

The Ferroelectric Reflectarray is fed quasi-optically so manifold losses are eliminated. Low loss ferroelectric phase enable an efficient system for long range or high data communications.

Calculated ferroelectric reflectarray and direct radiating MMIC phased array Antenna Gain as a function of the square root of the number of radiating elements.

Reflectarray Assumptions: 10 W, 40% efficient TWT, 4 dB loss phase shifters, 41 mW per channel controller power consumption

Direct Radiating MMIC Array Assumptions: 100 mW, 15 % efficient amplifiers, 85 % efficient power supply
Effect of Phase Shifter Loss on Antenna Noise Temperature

Assumes an antenna brightness temperature of 90 K

With a system noise temperature of \( \approx 500 \text{K} \) and assuming a scan loss of \( \cos(\theta)^{1.2} \) an array of 12,500 elements will produce a gain commensurate with a G/T specification of 15 dB/K
Prototype – Band 615 Element Ferroelectric Reflectarray System
(Aperture & Feed and Low Power Controller)

- 31 cm diameter active K-band reflectarray antenna
- 615 thin film ferroelectric phase shifters with integral microstrip radiators
- Custom 18.8 GHz dual-mode feed horn
- Very low power consumption (22 W) controller
Coupled Microstripline Ferroelectric Phase Shifter in $S_{21}$ Configuration

Phase shifters using paraelectric films on MgO substrates achieved $\approx 60\%$ dB insertion phase shift/loss.

0.3 mm MgO with a $\approx 400$ nm Laser Ablated $Ba_xSr_{1-x}TiO_3$ Film "Probe-able" phase shifter

"K-Band Phased Array Antennas Based on $Ba_{60}Sr_{40}TiO_3$ Thin Film Phase Shifters, R. Romanofsky et al., IEEE Trans. MTT, Vol. 48, No. 12, pp. 2504-2510, 2000"
Typical Coupled Microstripline (Baseline)
Ferroelectric Phase Shifter in Reflection Mode
Ba$_{30}$Sr$_{70}$TiO$_3$ (400 nm) Coupled Line Phase Shifter
Transient Response
Origin of ISI/BER Analysis

Formation of Inter-symbol Interference (ISI) due to Different Delays in Signal Components
Effect of Phase Shifter Behavior on BER

BER Curves of BPSK
Probability of Occurrence of a Particular Phase Shift
Given a 3721 element array and 16 possible States

Average Phase Shift = 116.5 degrees
Beam Updated in 2 degree increments (θ,φ)
Maximum Elevation Angle = 45° degrees
Maximum Azimuth Angle = 360 degrees
X-Band Hybrid Ferroelectric/Semiconductor Phase Shifter

Goal Achieved at X-Band!

Ka version in progress
Slow Wave (Synthetic Line) Ferroelectric Phase Shifter

Actual 19 Cell Slow-Wave Circuit with 200 \( \mu \)m coupled line varactors; Cell size=0.6 mm

0.125 dB/cell
Dissipative loss
Modeled (Lumped Equivalent Circuit) Performance of 16 cell Slow Wave Phase Shifter

16 cells with ideal varactors 0.45 (red), 0.39 (blue), and 0.25 (purple) pF yields 360 degrees of phase shift @ 20 GHz
Synthetic Line (slow-wave) Phase Shifter
Measured Data

$S_{ll}$ Measured Insertion Loss and Phase (T=295 K)

![Graph showing measured insertion loss and phase for different voltages.](image)
Synthetic Line (slow-wave) Phase Shifter
Measured Data

$S_{11}$ Measured Insertion Loss and Phase (T=250 K)
Effect of Temperature Variation on Insertion Phase

Insertion Phase as $f(T)$

- $T = 320$ K
- $T = 298$ K
- $T = 260$ K

$S_{11}$ measured data for 19 cell synthetic line phase shifter
Negative Group Delay or superluminal velocity have been predicted and demonstrated experimentally in systems with small transmission probability (high insertion loss), e.g. Notch filter:
Calculated Cut-off for Synthetic Line as a Function of LatticeSpacing with Capacitance and Impedance as Parameters
Prediction of Negative Differential Phase Shift (Positive Tau) (Capacitance Change 0.38 to 0.25 pF)
Negative Group Delay in A Synthetic Line Phase Shifter

START 20.6000000000 GHz
STOP 20.9000000000 GHz
The Ultimate Phase Shifter?

- Slow-Wave phase shifter offers better bandwidth compared to equivalent serial Coupled microstripline phase shifter
- Slow-Wave phase shifter promises lower loss – tunable structures are shunted across propagation path
- Combining 180 degree analog slow-wave section in cascade with switched virtual short may yield the best solution
- Intriguing group delay effects showing less in-band loss than previous demonstrations at low frequencies – applications?