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

R. R. Romanofsky
NASA Glenn Research Center

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.

Frequency-Agile Radio: Systems and Technologies, WMG 139

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

International Microwave Symposium
San Francisco, CA

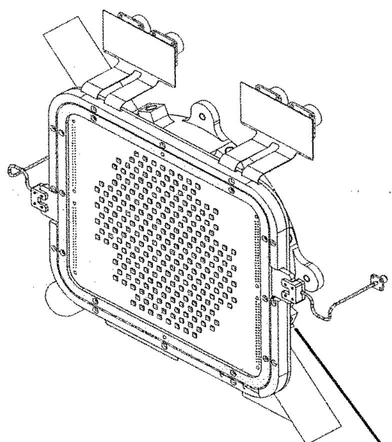
Robert. R. Romanofsky
NASA Glenn Research Center
Cleveland, OH

Outline

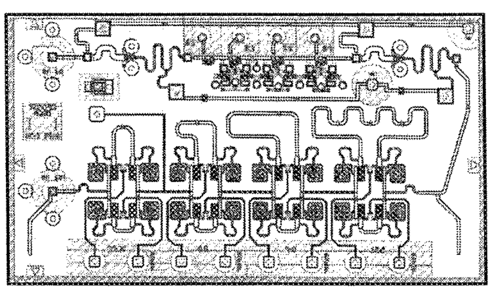
- Phased Array Antennas
  - Reflectarray Antenna Technology and Applications
  - Reflectaray Antenna Based On Thin Ferroelectric Film Phase Shifters
- Effect of Phase Shifter Insertion Loss on Reflectarray Performance
  - Efficiency
  - Sensitivity
- Effect of Phase Shifter Insertion Phase Characteristics on Reflectarray Performance
  - Impact of transient during beam evolution
  - Modulo 2π 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

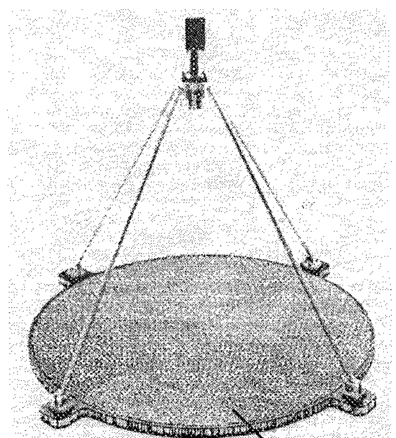


Gain: 29 dB (Limited)
Watts Consumed/dB EIRP: 7.2

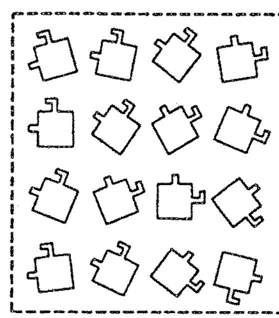


GaAs MMIC Phase Shifters

JPL 0.5 m *Fixed* Beam Ka-Band Reflectarray

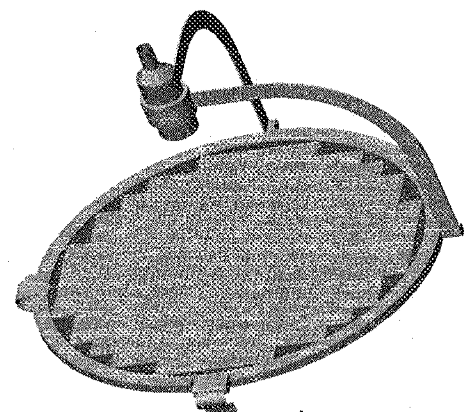


Gain: 42 dB (Scalable)
Watts Consumed/dB: N/A

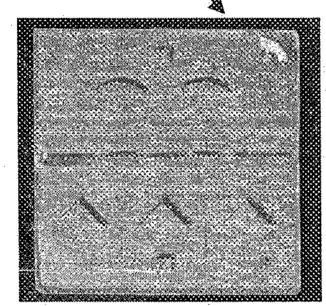


Rotated Patch Elements

X-Band ~1m *Scanning*
Ferroelectric Reflectarray



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



Thin Film Ferroelectric
Coupled Line Phase Shifters

What is a Reflectarray?

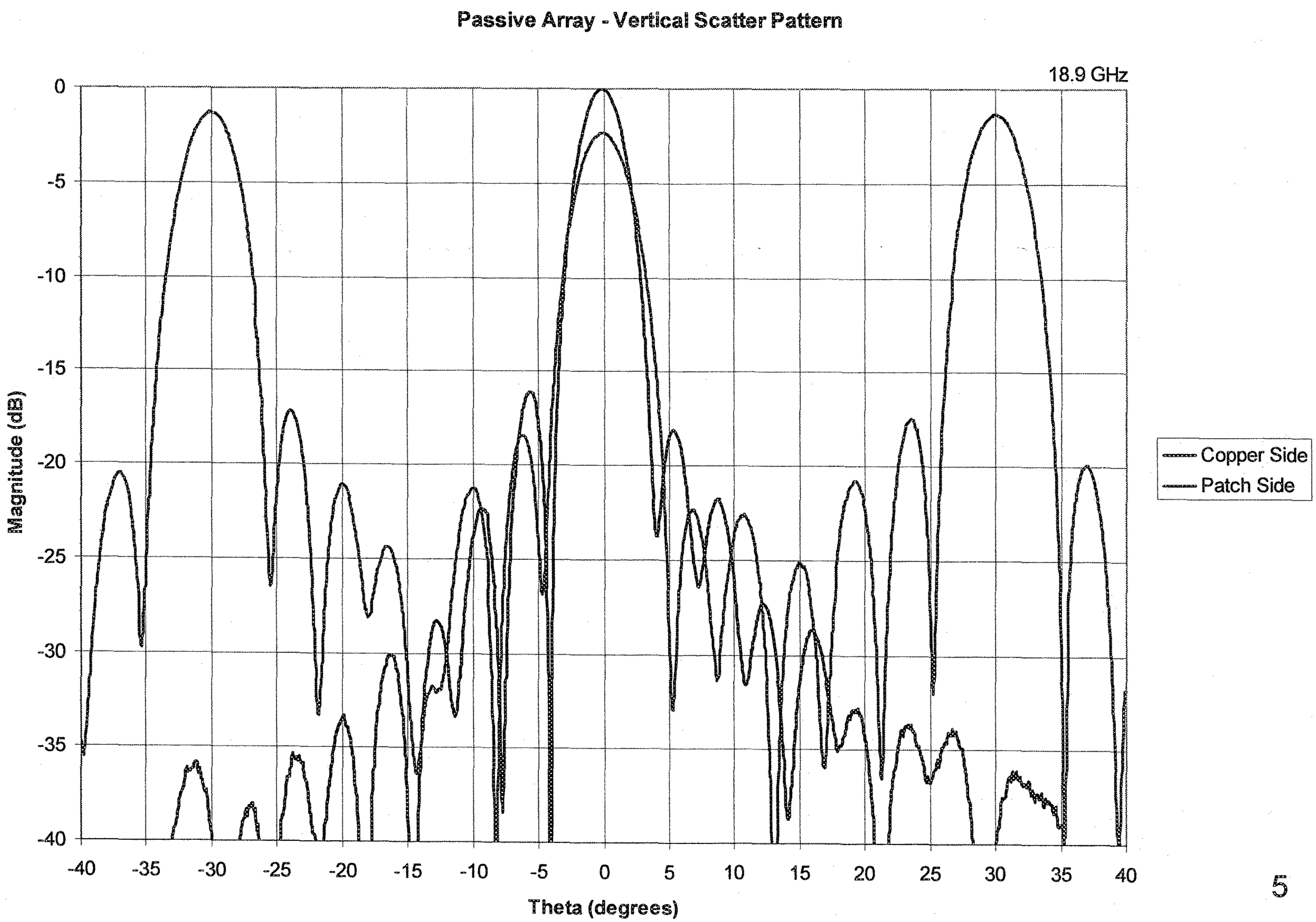
Technology Description:

- 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 ≈10 μm 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

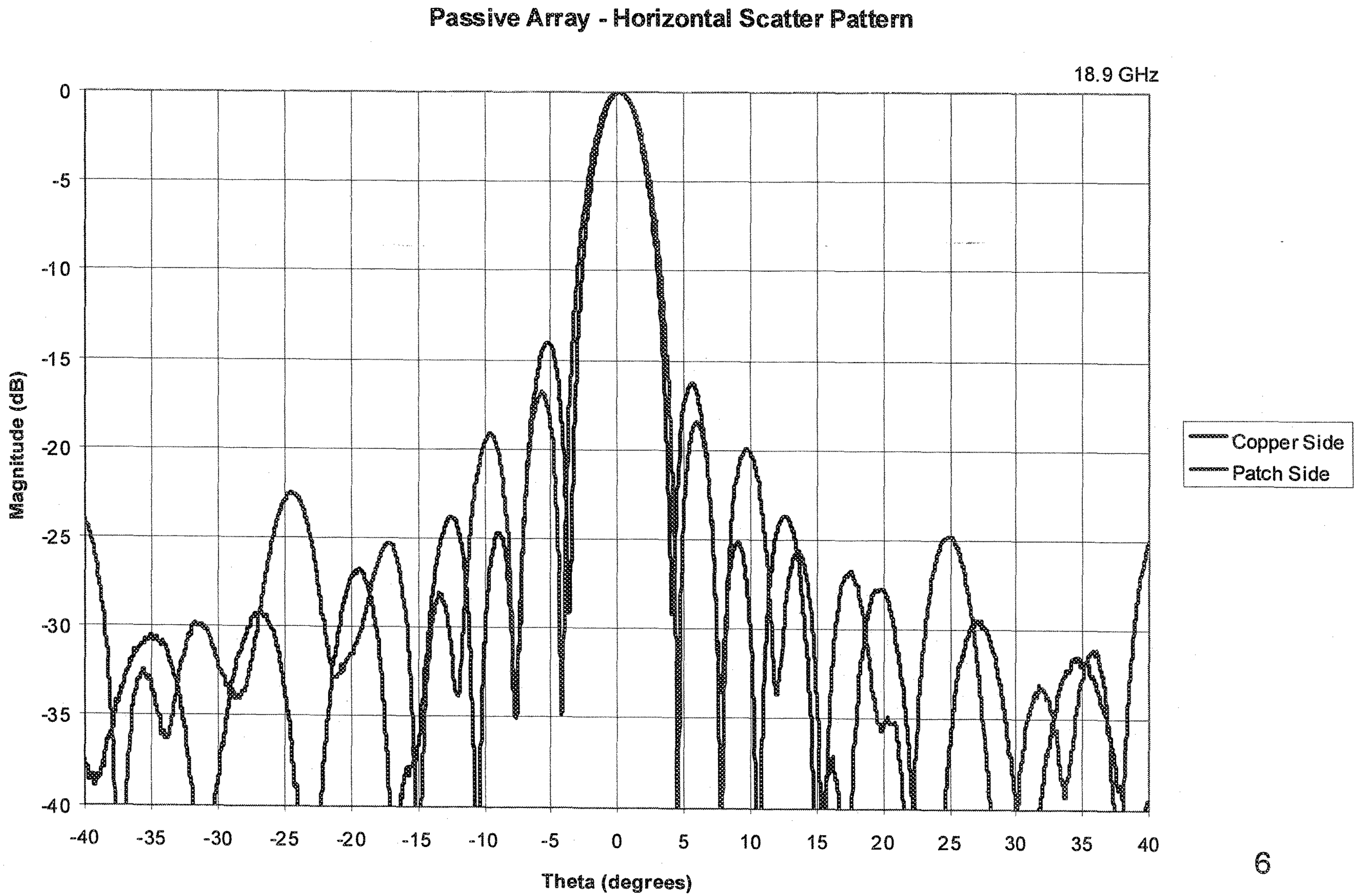
• Potential benefits

- 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

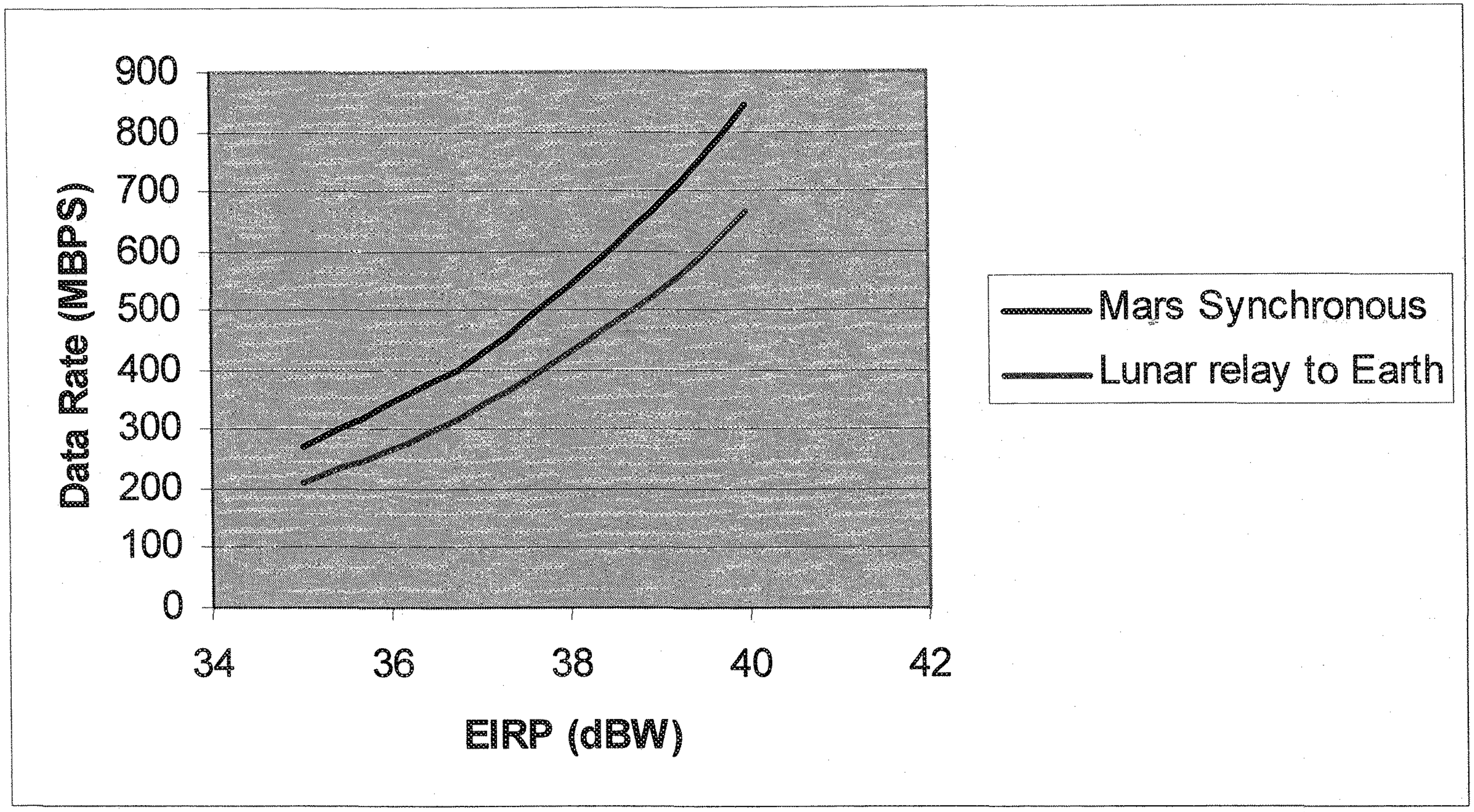
208 Element Passive Reflectarray E-Field Pattern (Vertical Polarization)



~~128~~ 208 Element Passive Reflectarray E-Field Pattern (Horizontal Polarization)

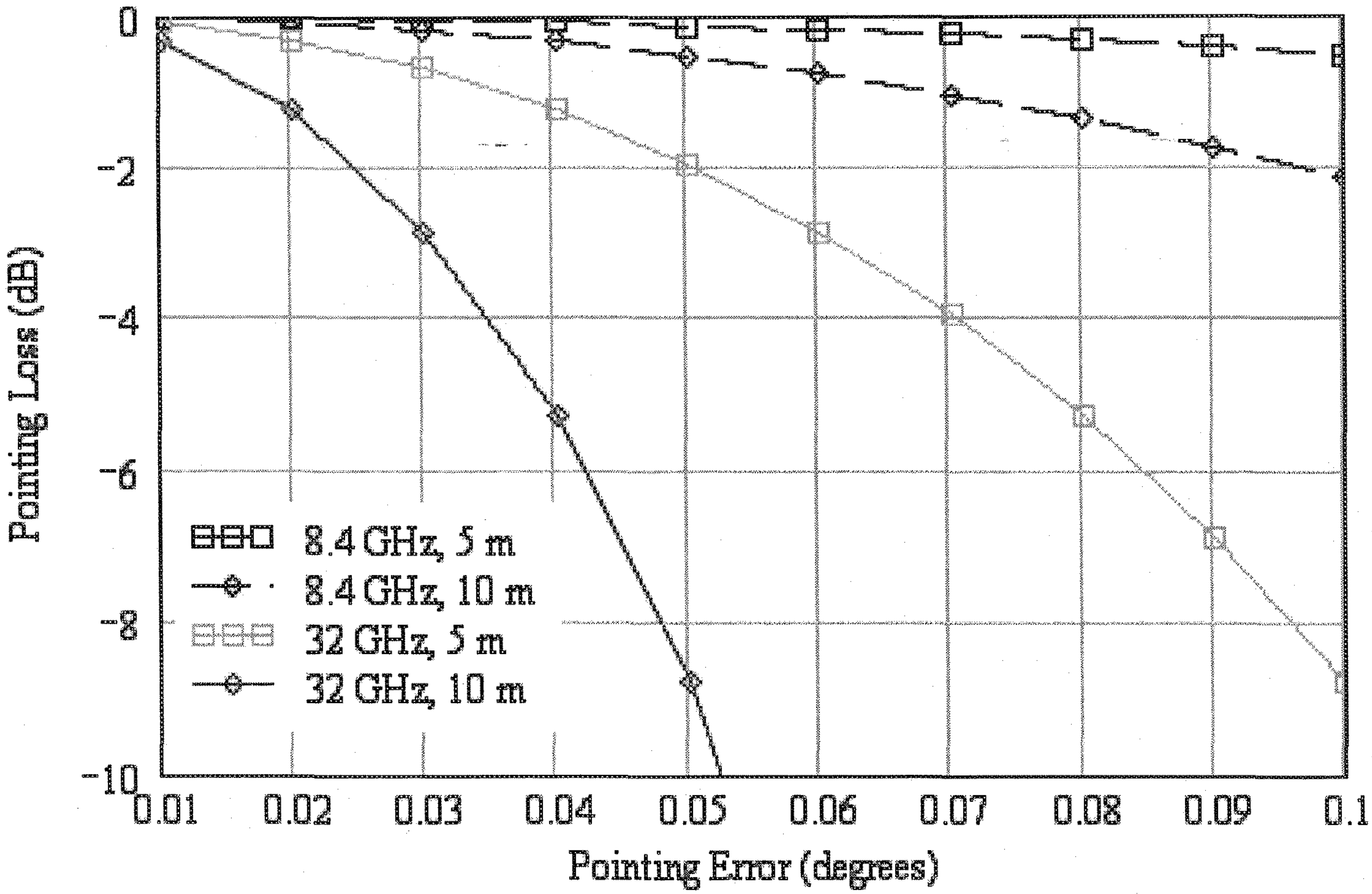


Steerable Reflectarray Applications @ 32 GHz

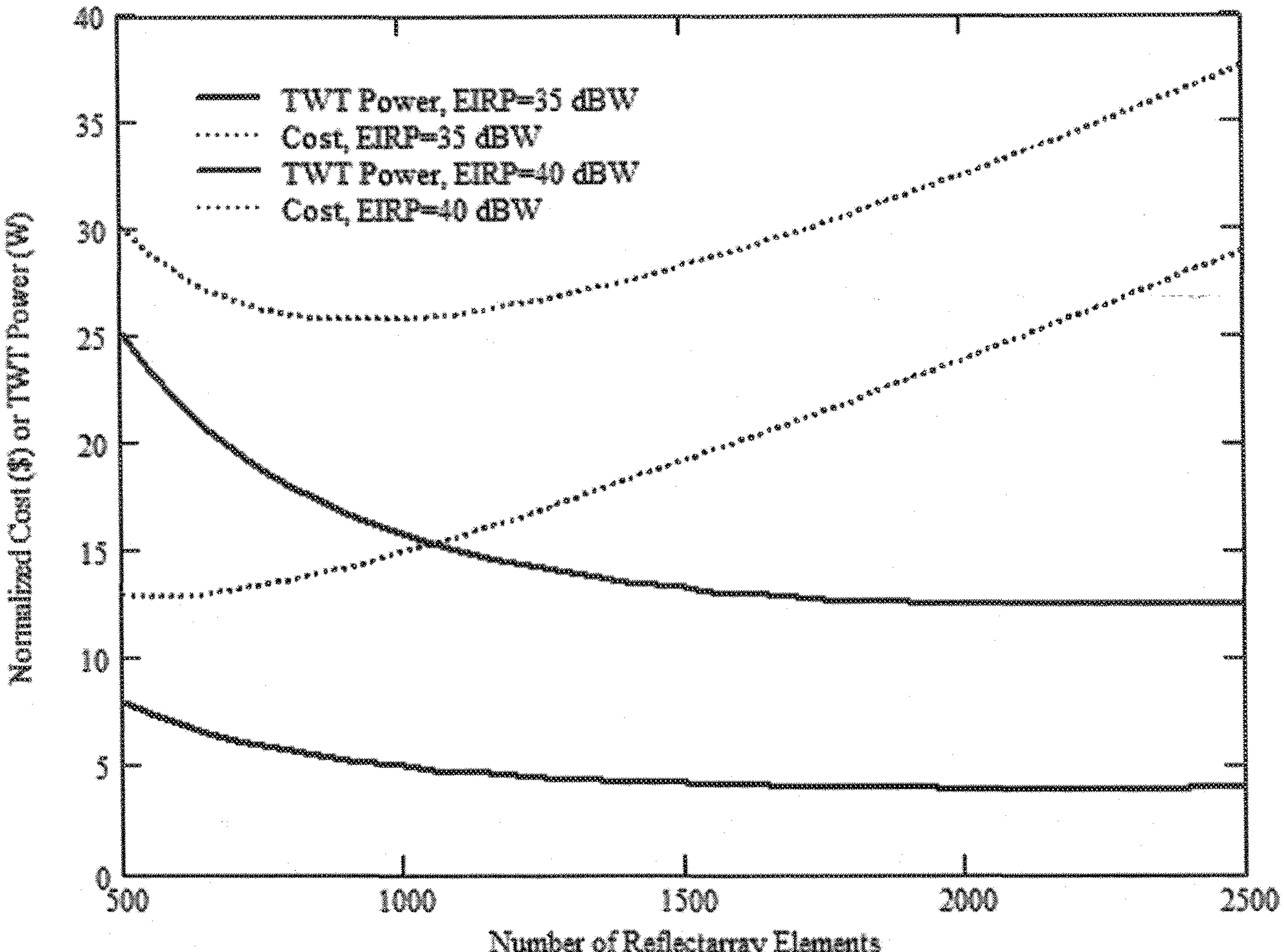


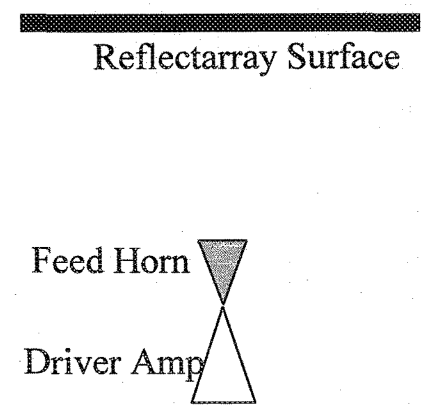
- e.g. Rover to MSO Relay Satellite with 1 meter receive aperture
- Single 34 meter DSN antenna
- Also, feed for inflatable to provide several beamwidths steering

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.



Cost and Drive Amplifier Power Vs. Array Size

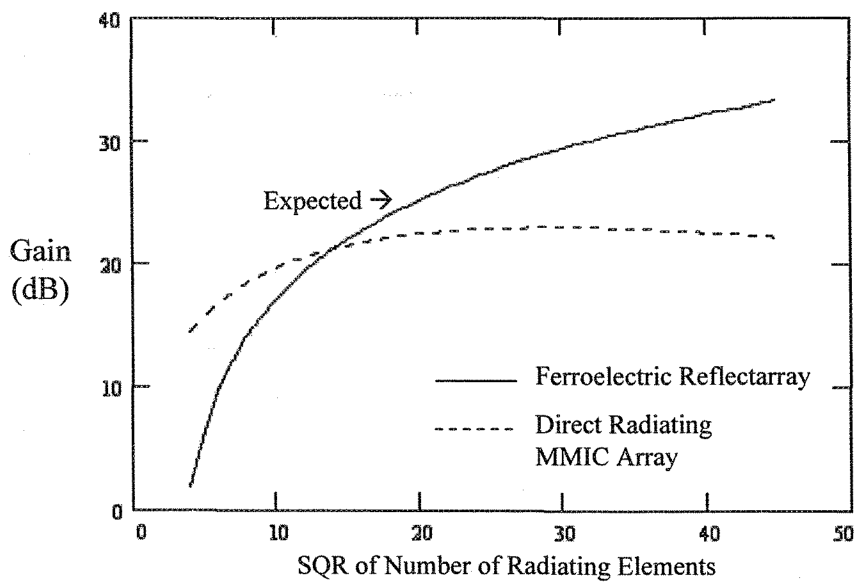




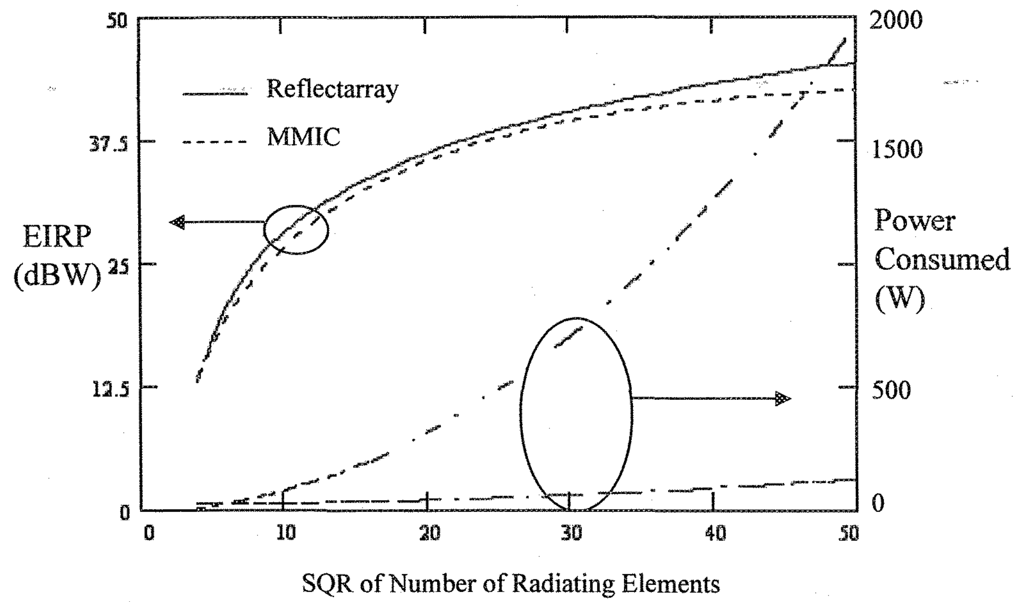
- TWT power diminishes with element count but eventually offset by ISI loss
- Reflectarray cost dominated by ferroelectric materials cost
- TWT cost assumed proportional to output power

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.



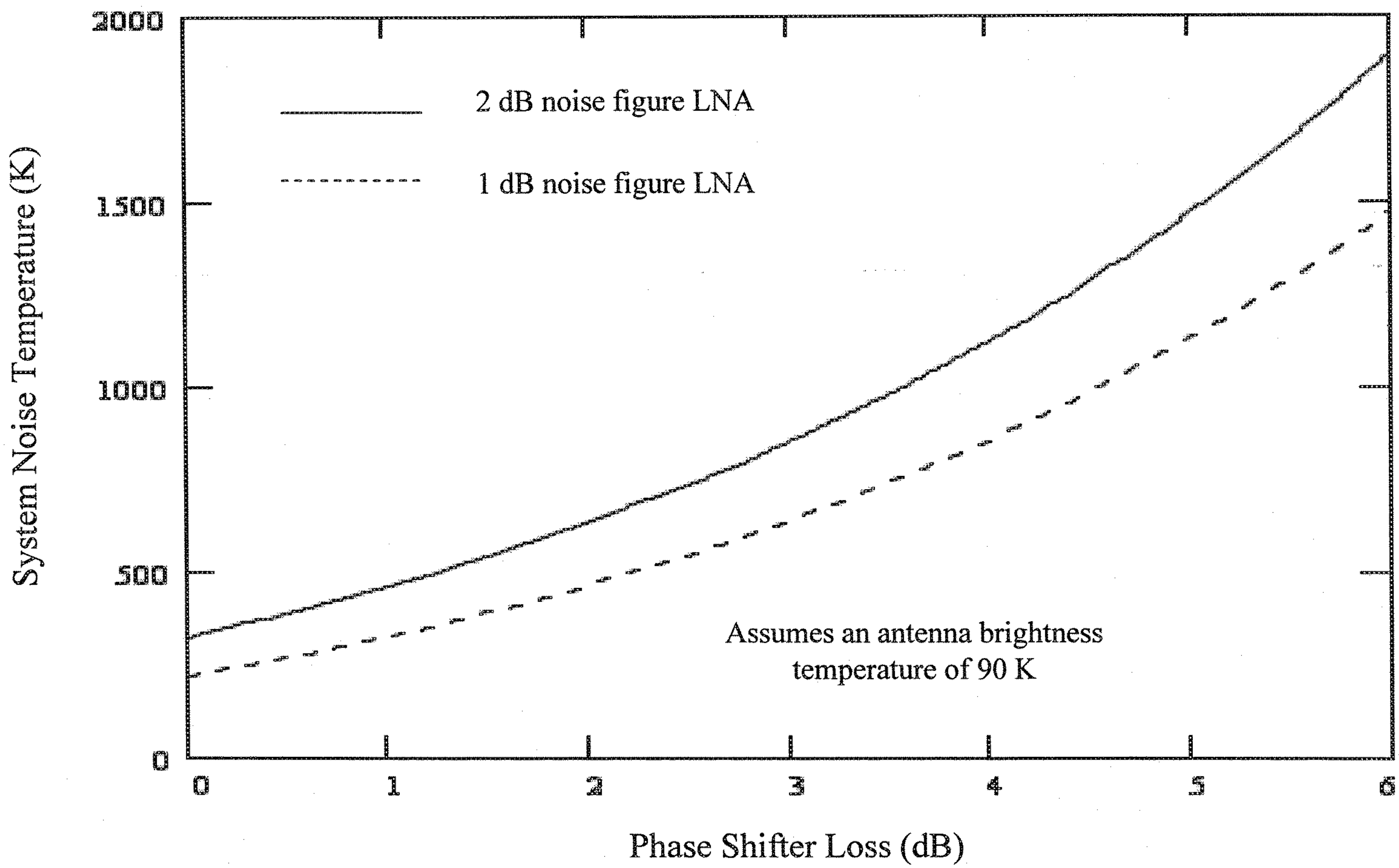
Calculated ferroelectric reflectarray and direct radiating MMIC phased array Antenna Gain as a function of the square root of the number of radiating elements.



Calculated EIRP and Power Consumption for a Ferroelectric reflectarray and a direct radiating MMIC phased array as a function of the square root of the number of radiating elements.

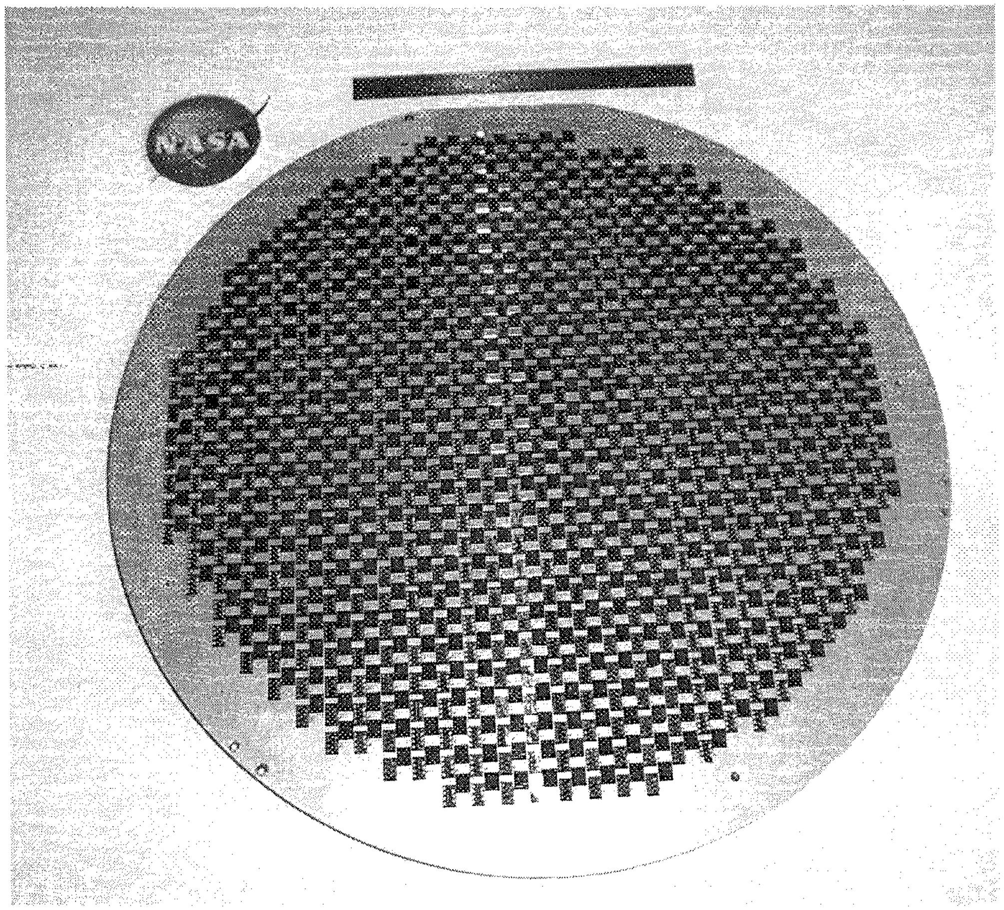
Reflectarray Assumptions: 10 W, 40% efficient TWT, 4 dB loss phase shifters, 41 mW per channel controller power consumption
Direct Radiating MMIC Array Assumptions: 100 mW, 15 % efficient amplifiers, 85 % efficient power supply

Effect of Phase Shifter Loss on Antenna Noise Temperature



With a system noise temperature of $\approx$500K 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)



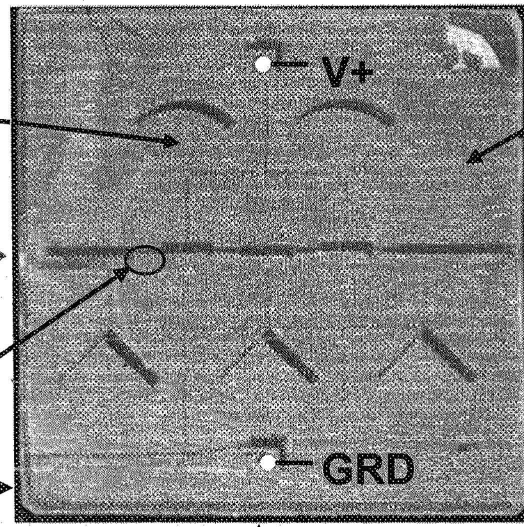
- 31 cm diameter active K-band reflectarray antenna
- 615 thin film ferroelectric phase shifters with integral microstrip radiators
- Custom 18.8 GHz dual-mode feed horn
- Very low power consumption (22 W) controller

Coupled Microstripline Ferroelectric Phase Shifter in S_{21} Configuration

Radial Stub Bias Tee

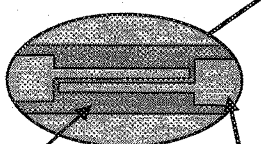
Magnesium Oxide Substrate (500 μm Thick)

Ferroelectric Phase Shifter Element (1 of 4)



180 degrees total phase shift at 350 volts bias

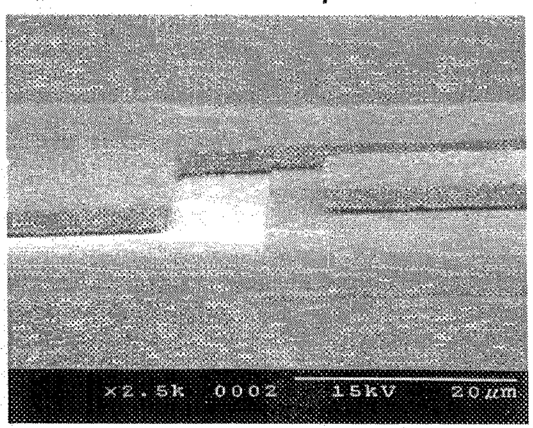
1 cm

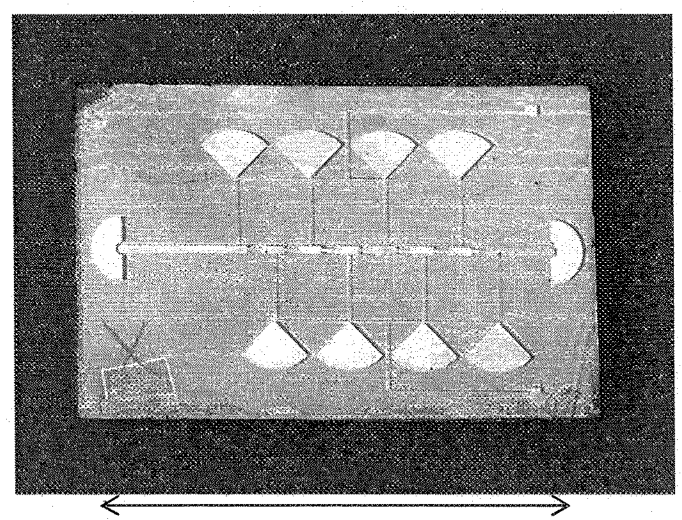


Cr-Au, 2μm

Laser Ablated Ba50Sr50TiO3 0.35 μm film

Phase shifters using paraelectric films on MgO substrates achieved ≈60°/dB insertion phase shift/loss.



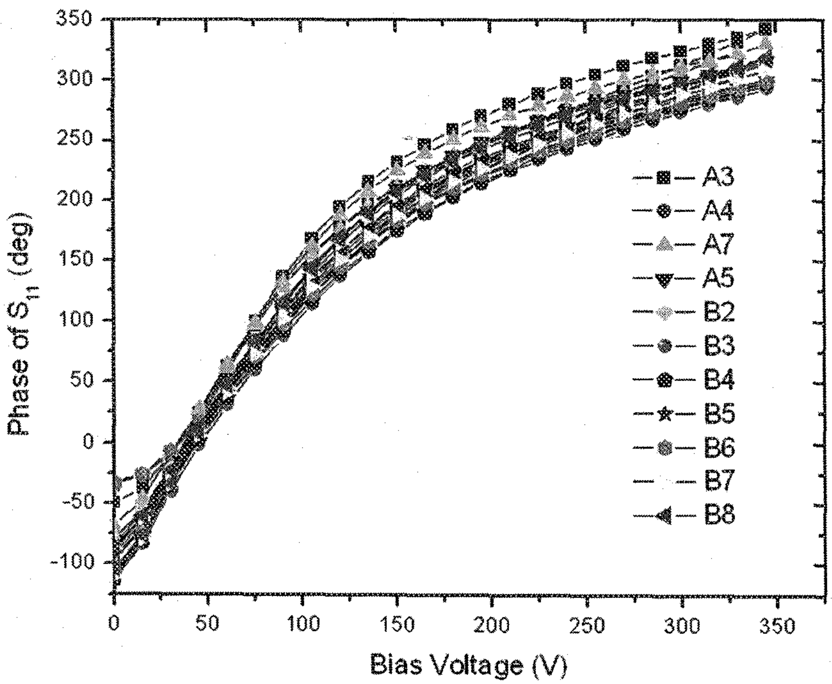


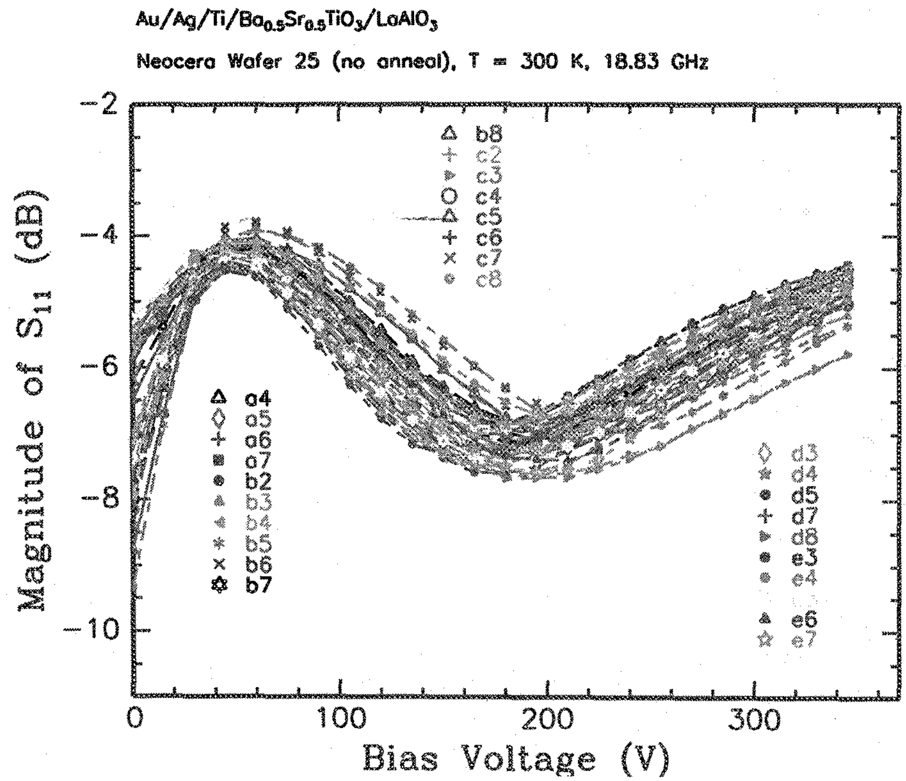
1.2 cm

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

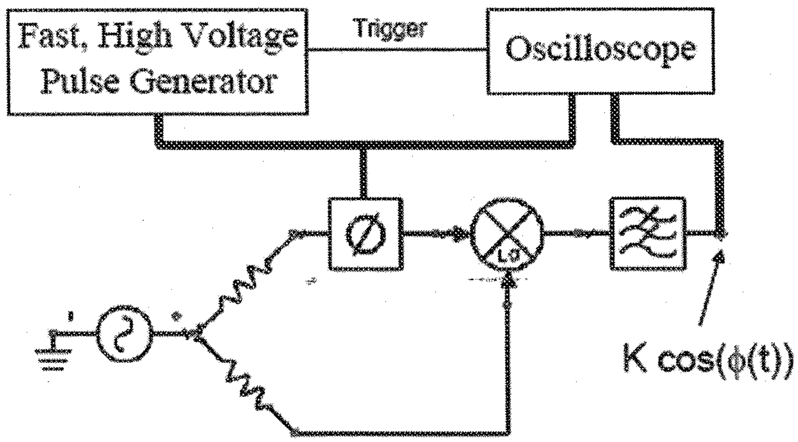
"K-Band Phased Array Antennas Based on $Ba_{60}Sr_{40}TiO_3$ Thin Film Phase Shifters, R. Romanofsky et al., IEEE Trans. MTT, Vol. 48, No. 12, pp. 2504-2510, 2000

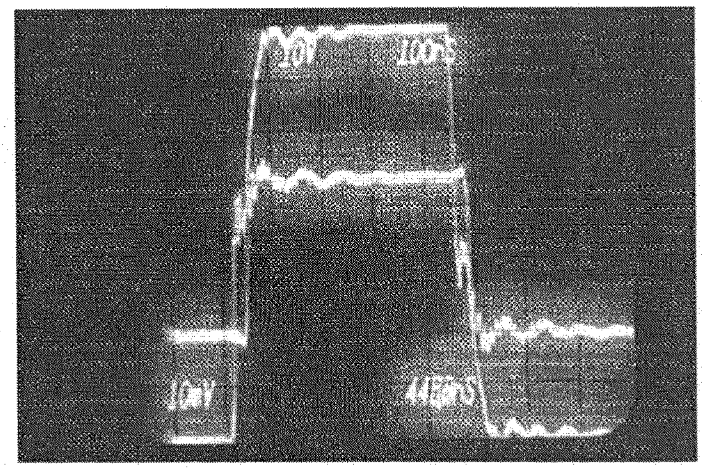
Typical Coupled Microstripline (Baseline) Ferroelectric Phase Shifter in Reflection Mode

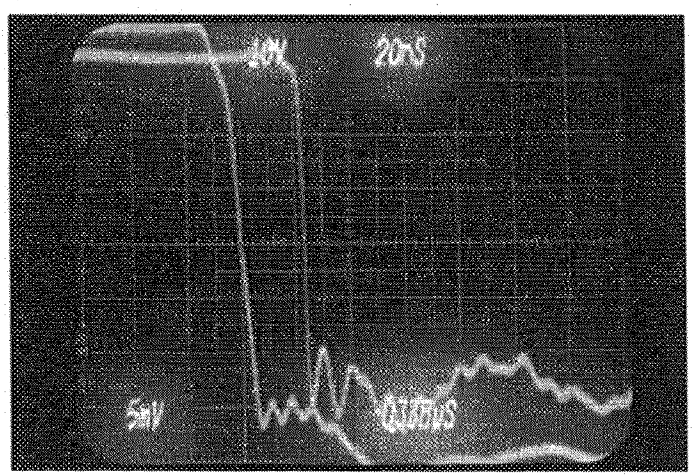


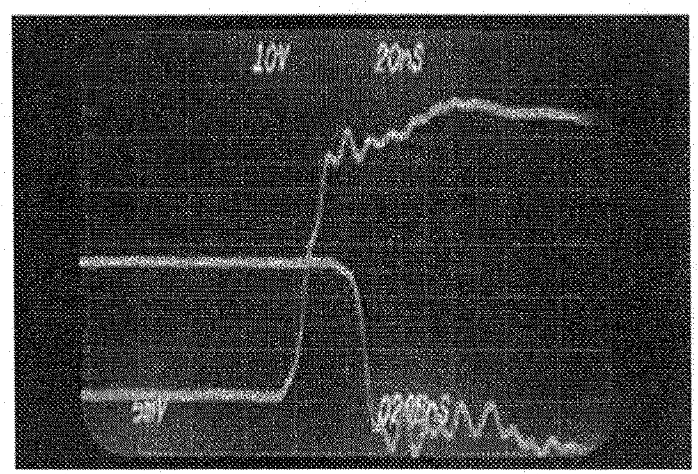


$Ba_{30}Sr_{70}TiO_3$ (400 nm) Coupled Line Phase Shifter Transient Response

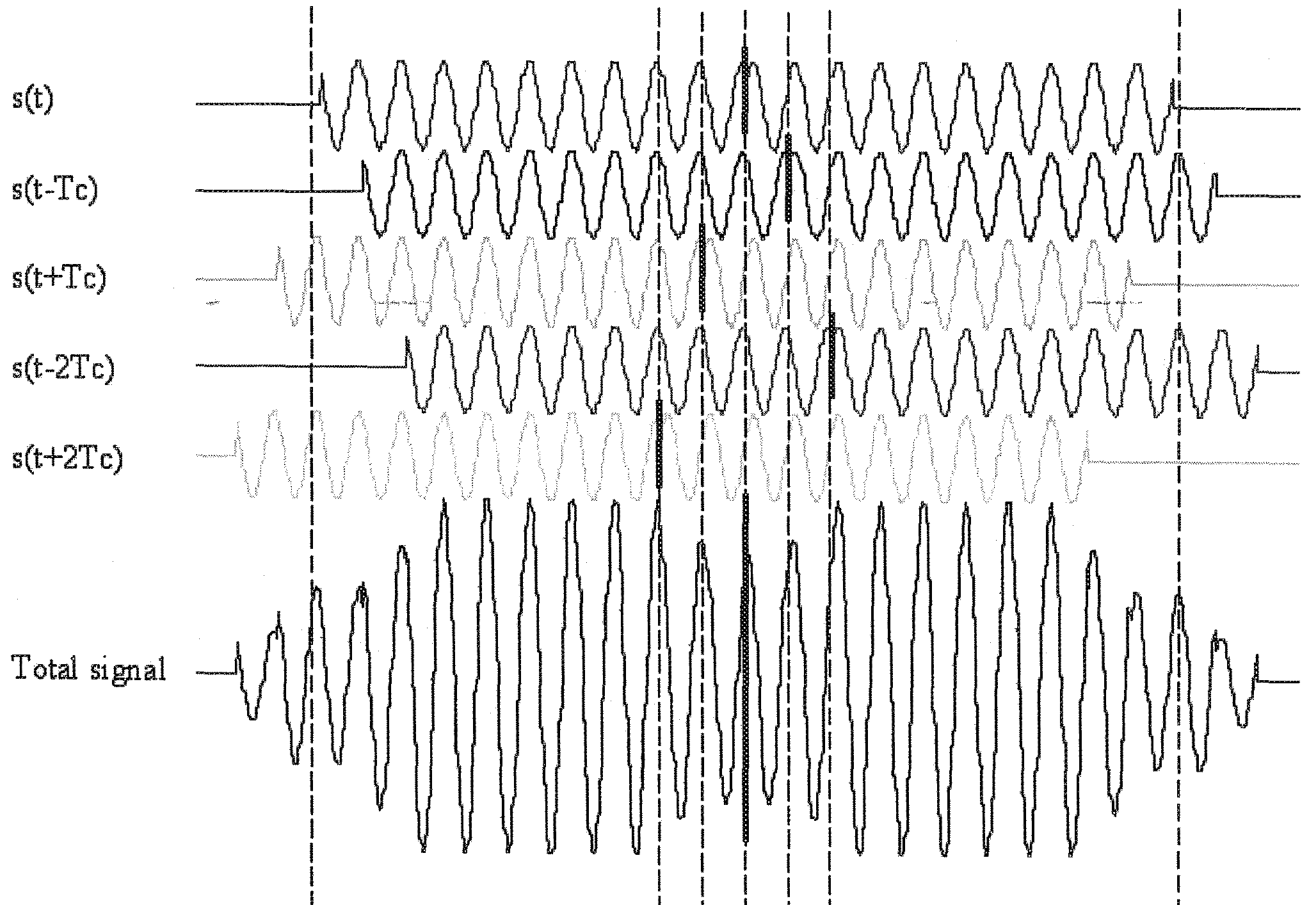






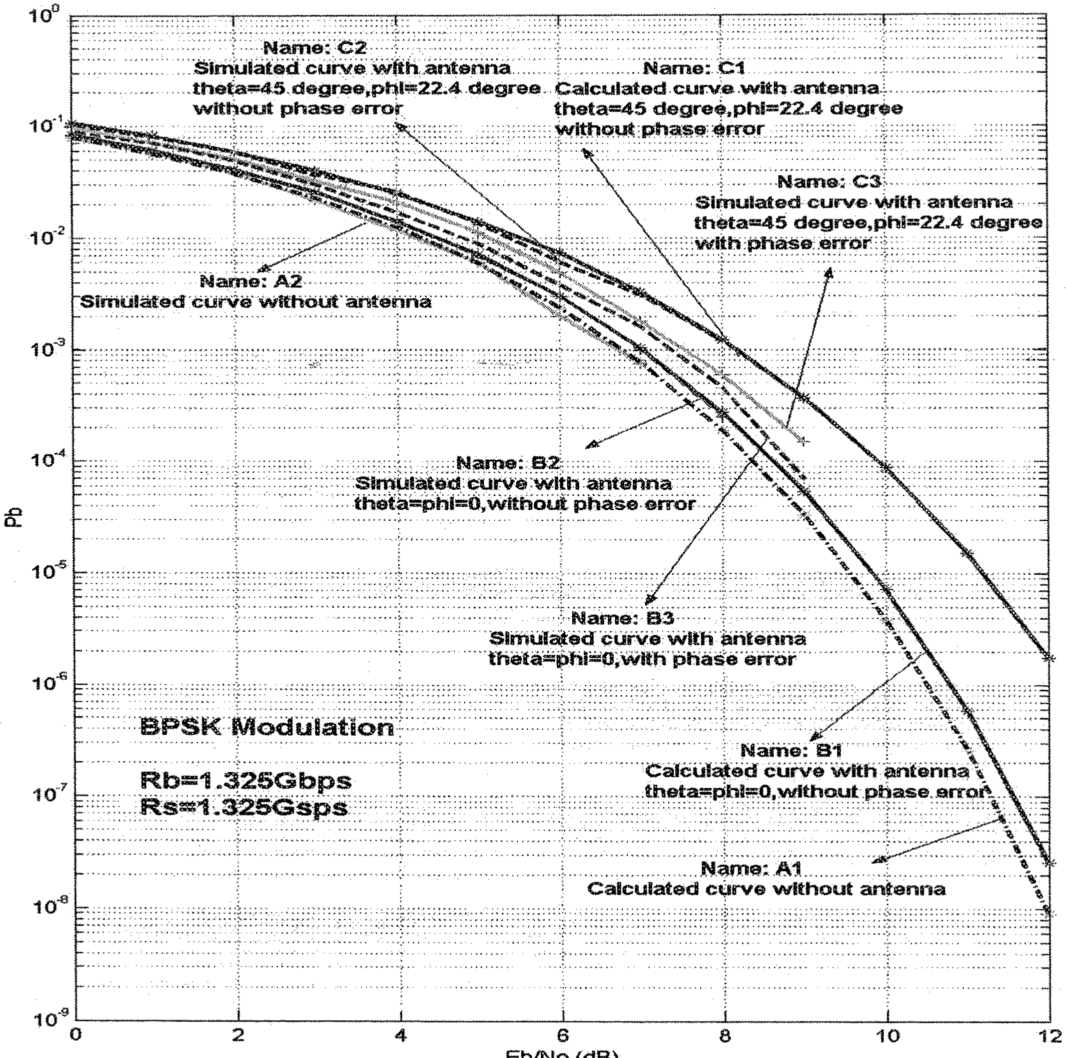


Origin of ISI/BER Analysis



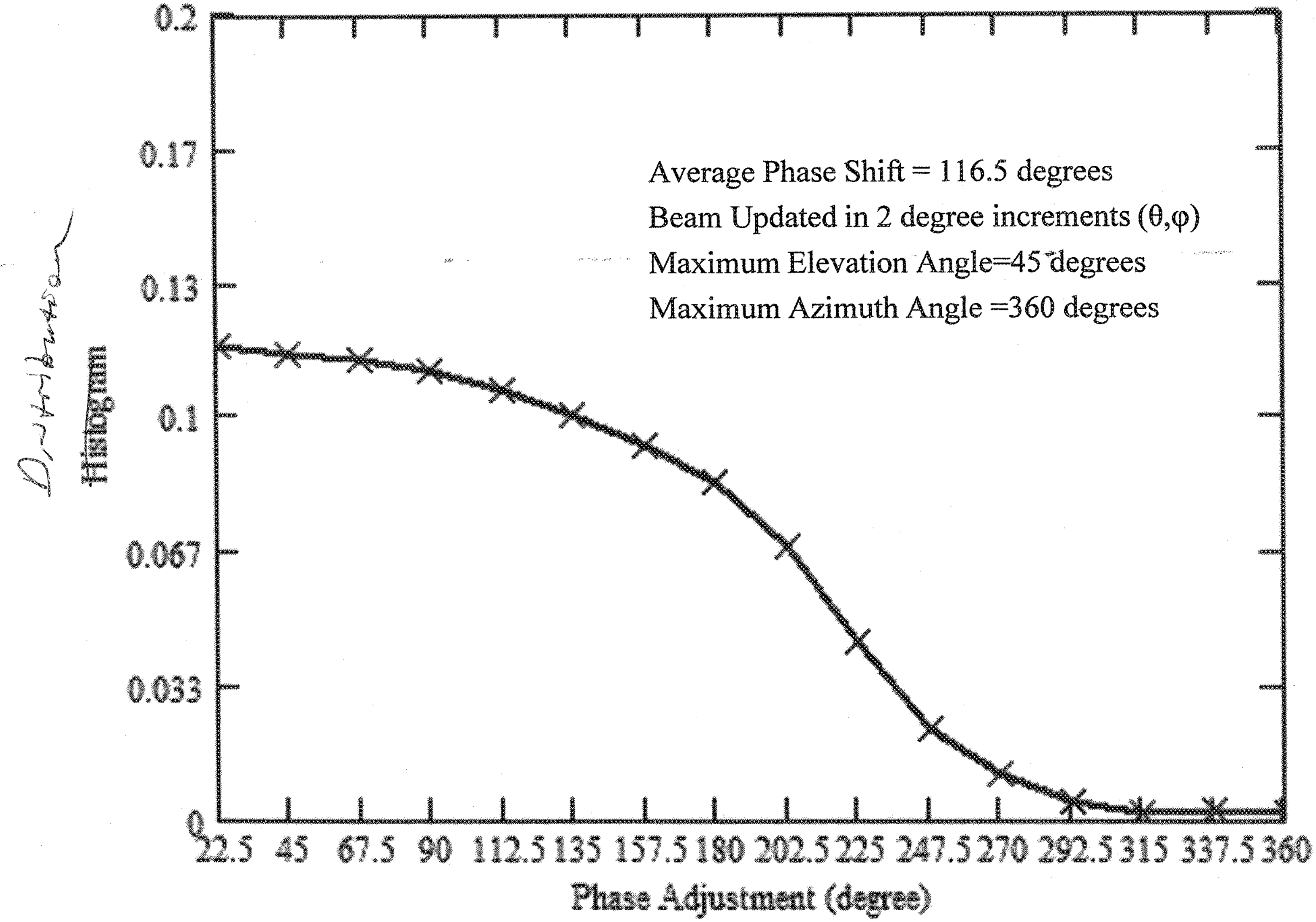
Formation of Inter-symbol Interference (ISI) due to Different Delays in Signal Components

Effect of Phase Shifter Behavior on BER

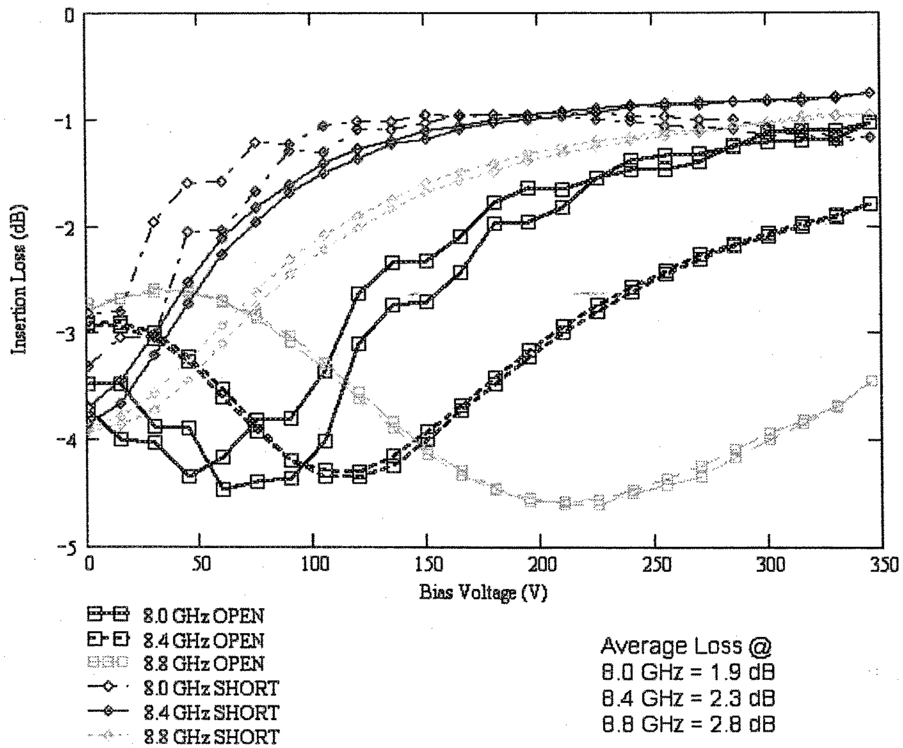


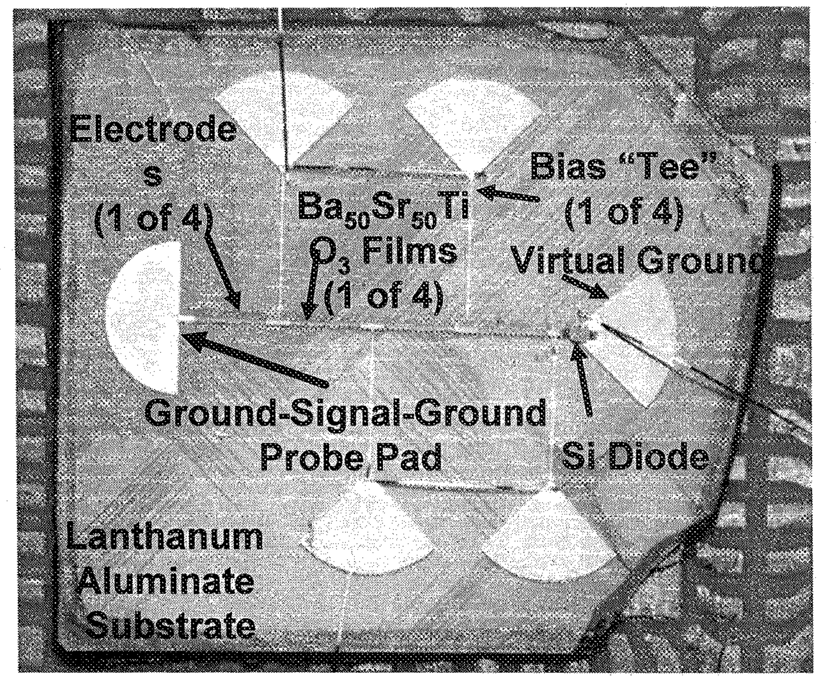
BER Curves of BPSK

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



X-Band Hybrid Ferroelectric/ Semiconductor Phase Shifter



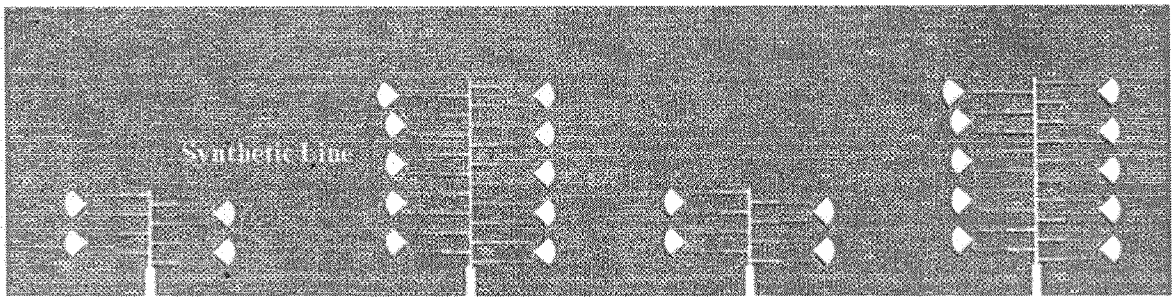


Photograph of prototype X-band phase shifter with 4 coupled microstripline sections and Si diode switch, which produced ≈310° of phase shift with 2.5 dB insertion loss.

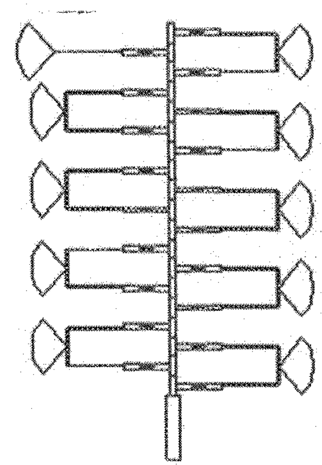
Goal Achieved at X-Band !

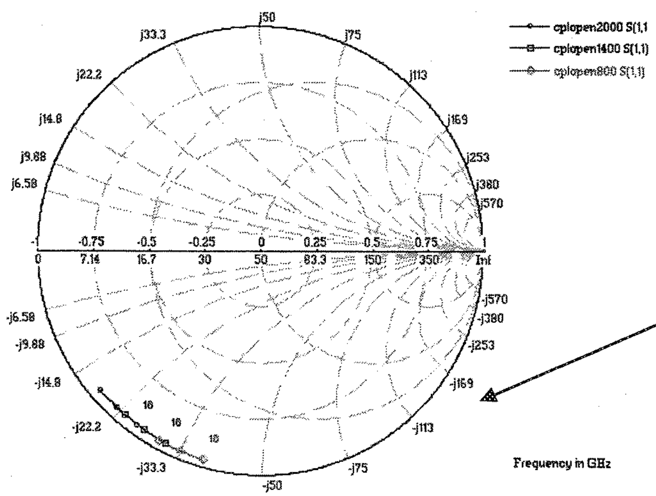
Ka version in progress

Slow Wave (Synthetic Line) Ferroelectric Phase Shifter



Actual 19 Cell Slow-Wave Circuit with 200 μm coupled line varactors; Cell size=0.6 mm

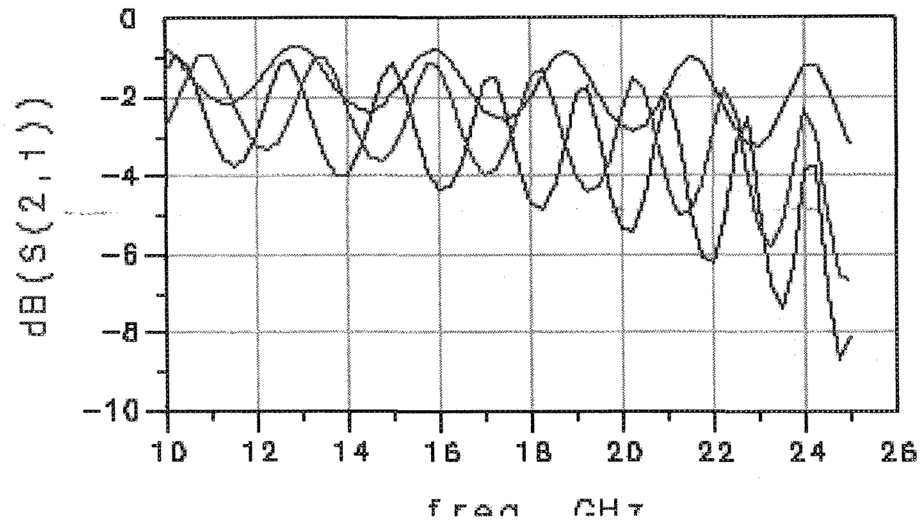


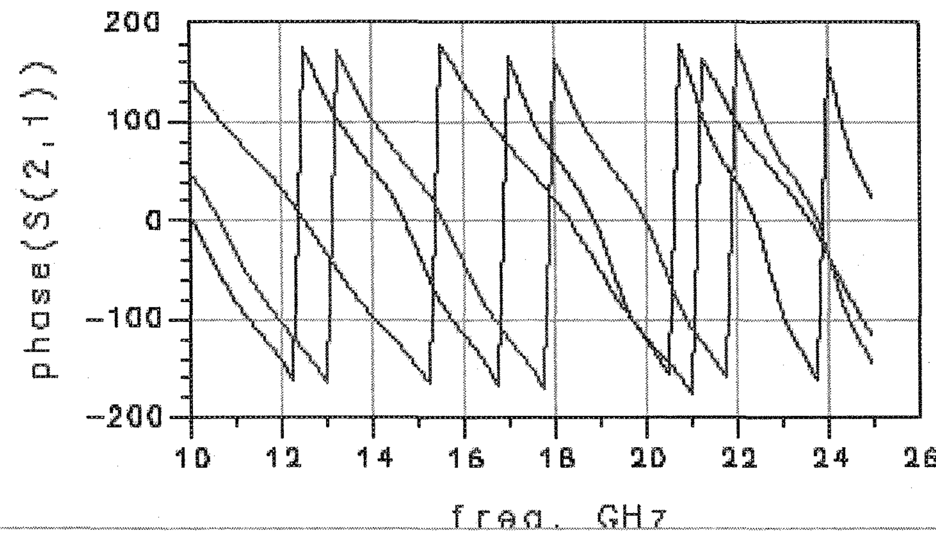


0.125 dB/cell Dissipative loss

Modeled (Lumped Equivalent Circuit) Performance of 16 cell Slow Wave Phase Shifter

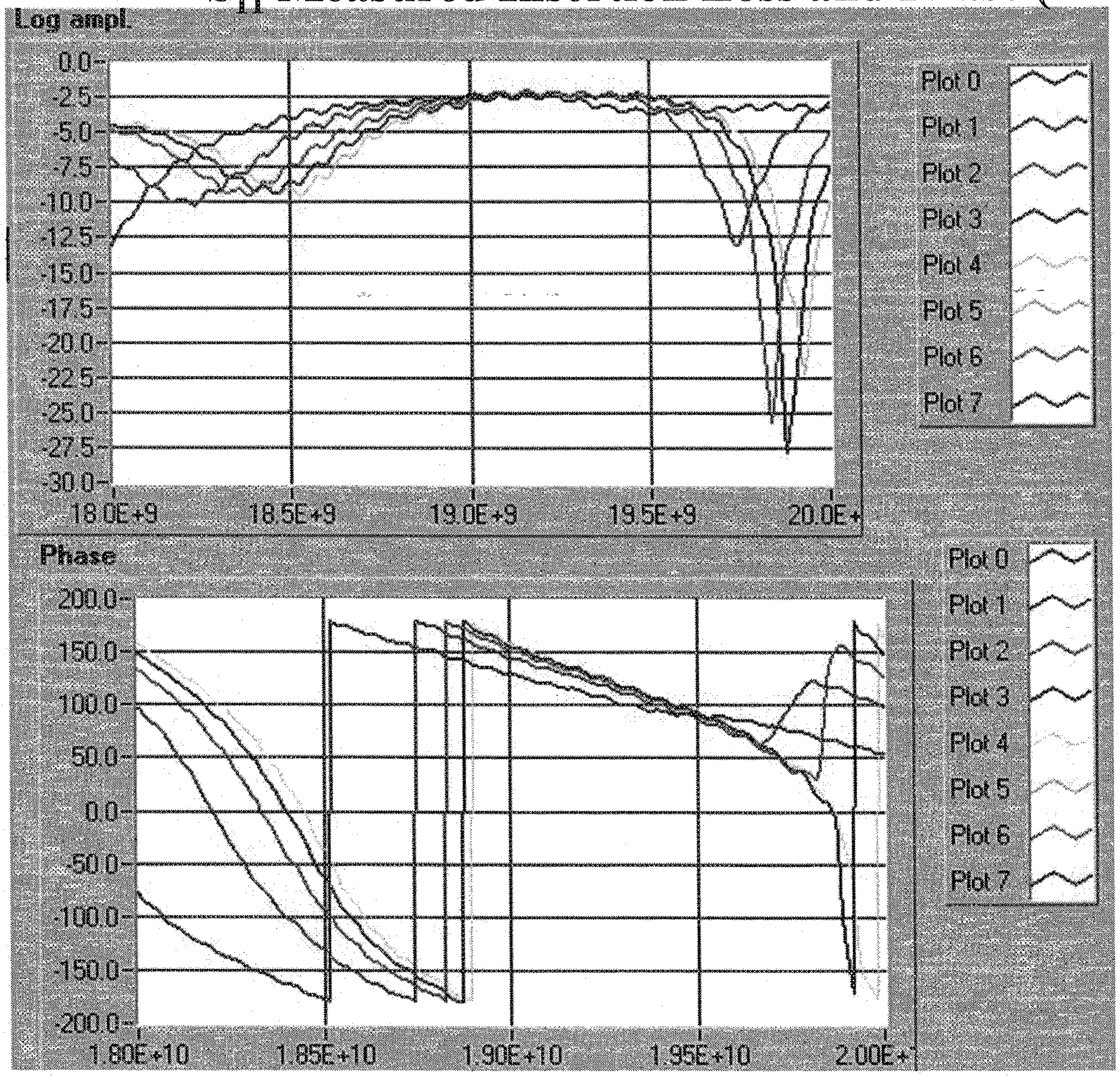
16 cells with ideal varactors 0.45 (red), 0.39 (blue), and 0.25 (purple) pF yields 360 degrees of phase Shift @ 20 GHz





Synthetic Line (slow-wave) Phase Shifter
Measured Data

S_{11} Measured Insertion Loss and Phase (T=295 K)

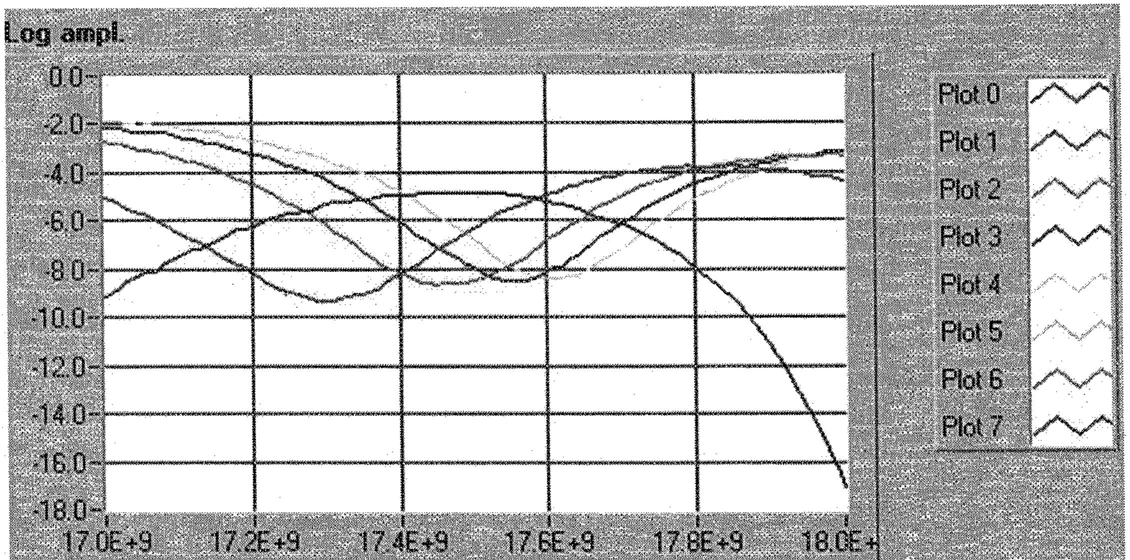


0 V
50 V
100 V
150 V
200 V

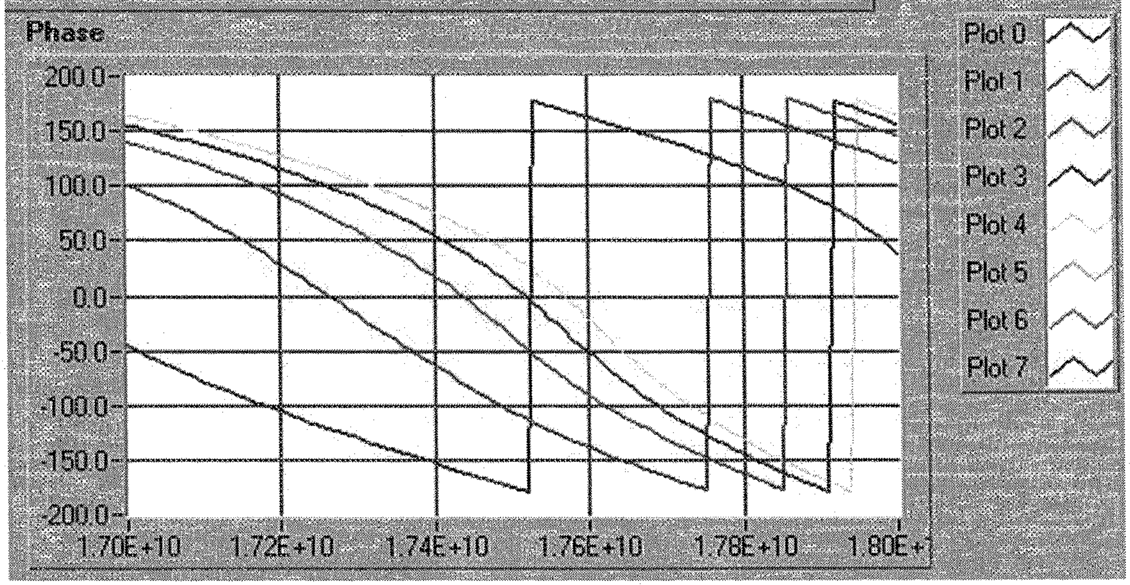
0 V
50 V
100 V
150 V
200 V

Synthetic Line (slow-wave) Phase Shifter
Measured Data

S_{11} Measured Insertion Loss and Phase (T=250 K)

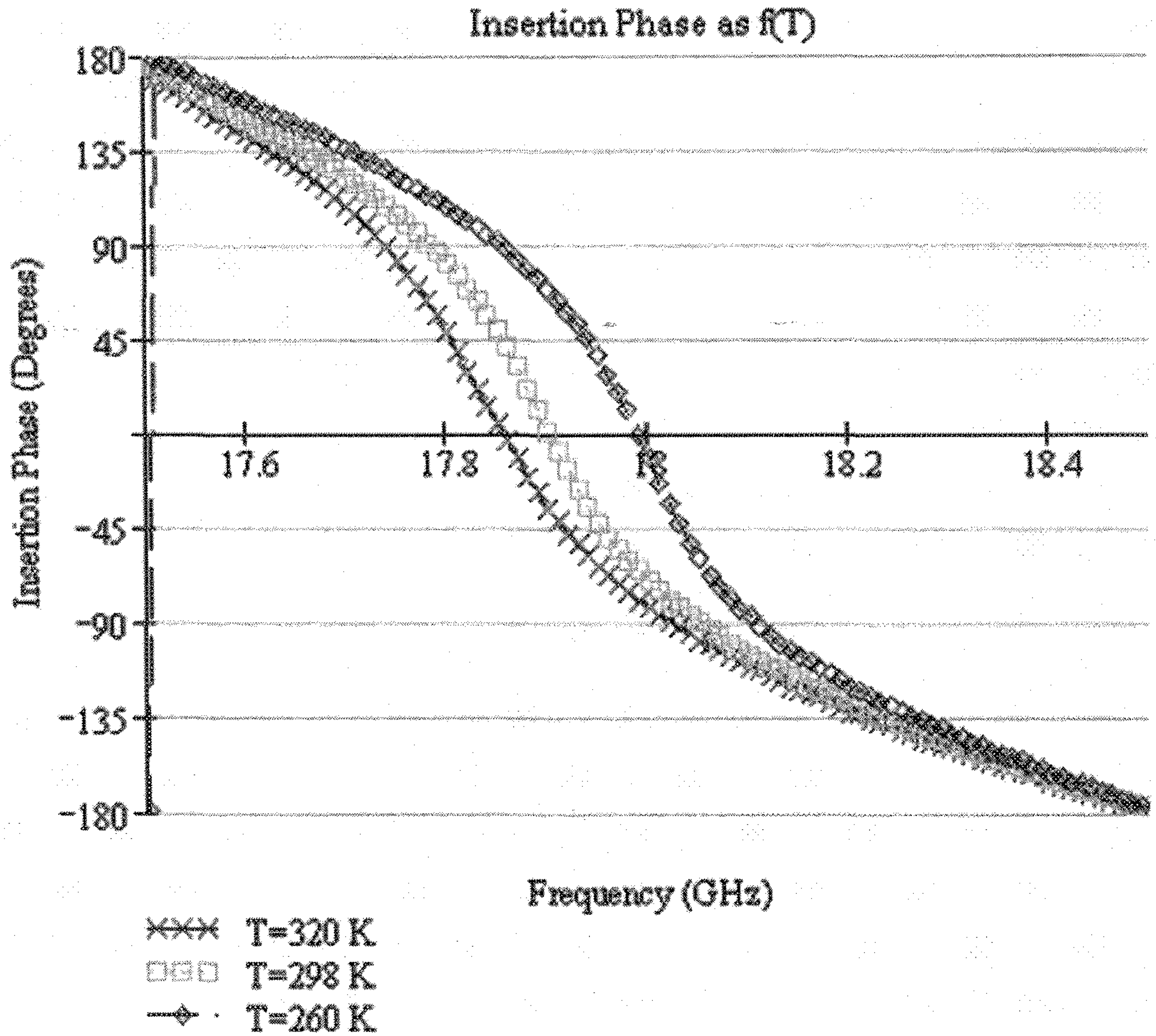


0 V
50 V
100 V
150 V
200 V



0 V
50 V
100 V
150 V
200 V

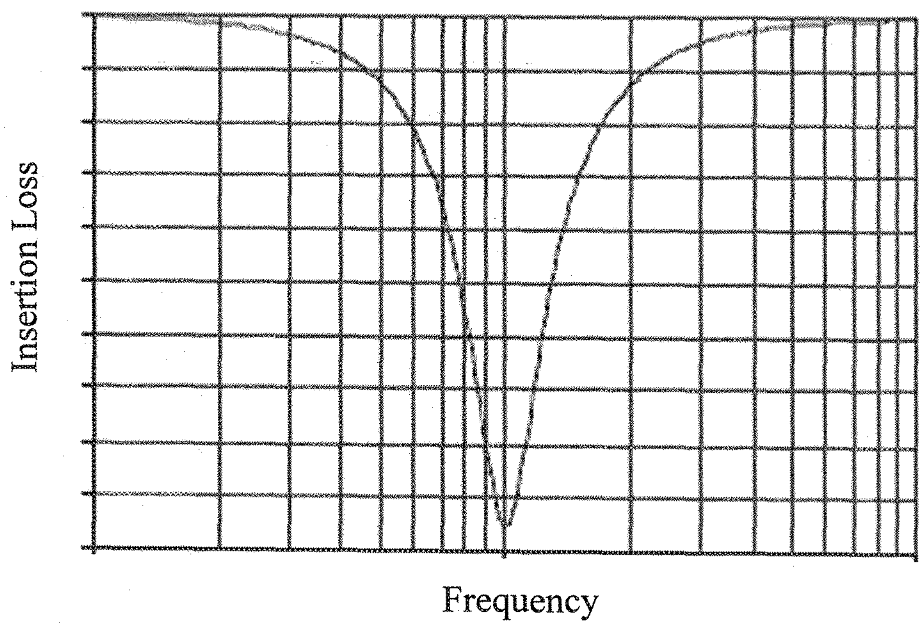
Effect of Temperature Variation on Insertion Phase

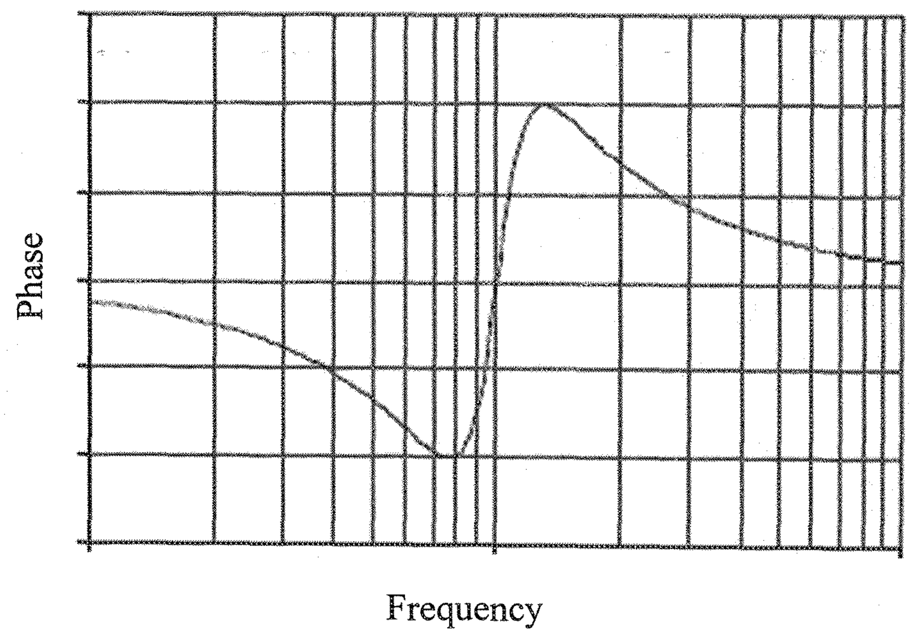


[1]S_{11} measured data for 19 cell synthetic line phase shifter

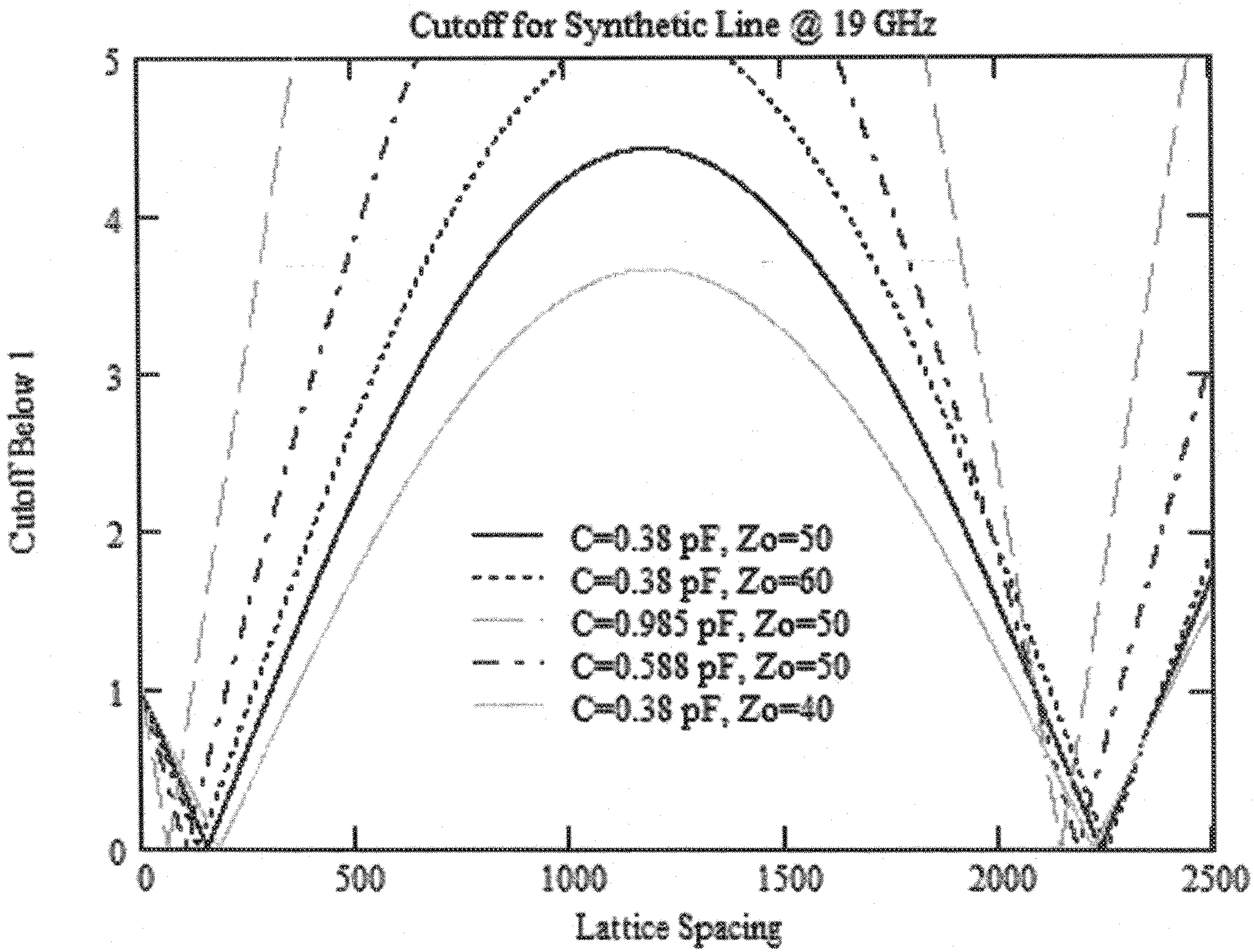
Negative Group Delay

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:

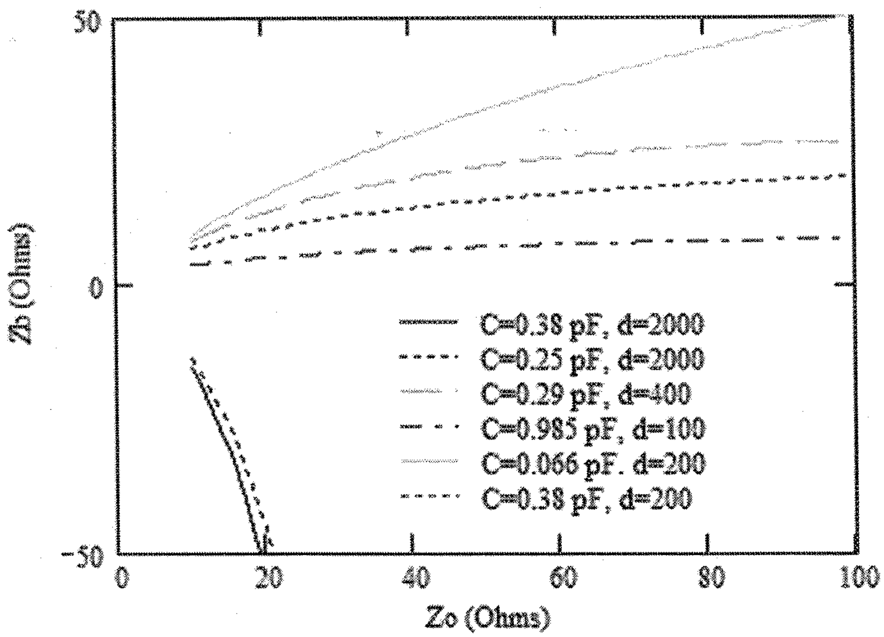


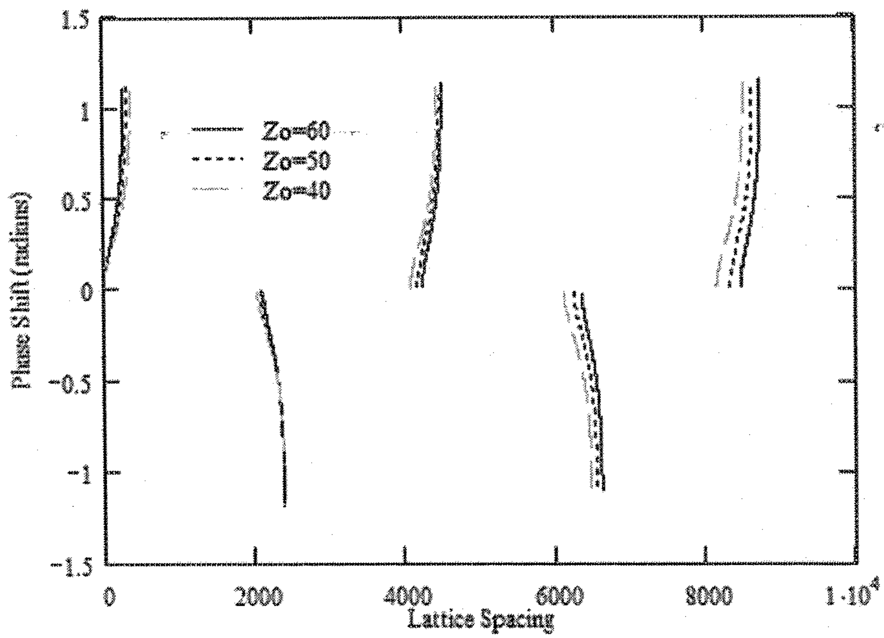


Calculated Cut-off for Synthetic Line as a Function of LatticeSpacing with Capacitance and Impedance as Parameters

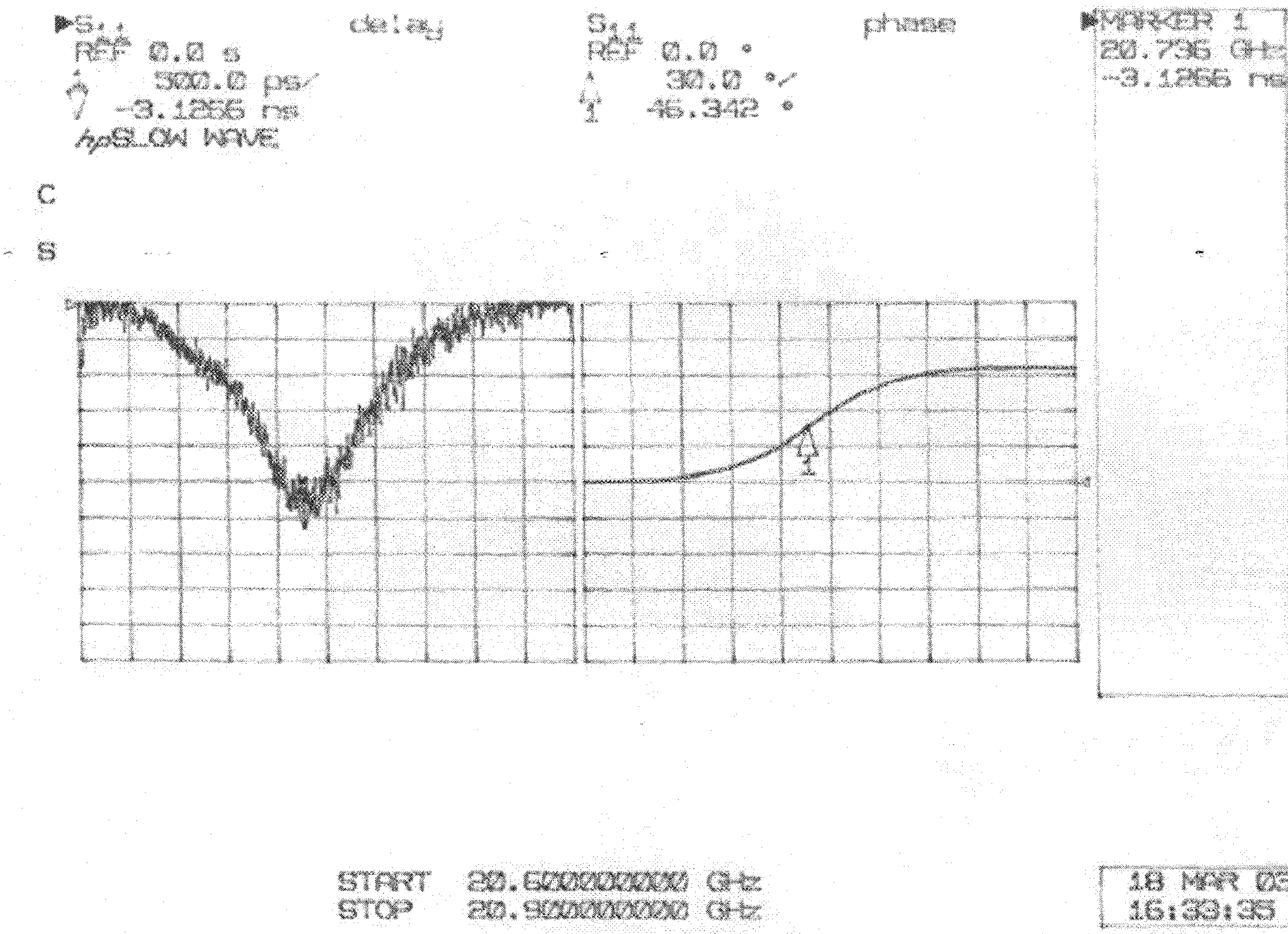


Prediction of Negative Differential Phase Shift (Positive Tau) (Capacitance Change 0.38 to 0.25 pF)





Negative Group Delay in A Synthetic Line Phase Shifter



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?