WFL: Microwave Applications of Thin Ferroelectric Films

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Outline:

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- A Statistical Analysis of Ferroelectric Film Quality
- Phase Shifters
- Oscillators
- The Reflectarray Antenna
- Radiation Testing
- Ferroelectric Reflectarray Critical Components Space Experiment
- A Piezoelectric Transformer Driver for Ferroelectric Devices
- An Agile Microstrip Patch Antenna
- “Strange” Results
  - 1/f noise
  - Anomalous Magnetoresistive Effect
Crystal Structure of Displacement Type Ferroelectrics

(a) Crystal lattice cell of BaTiO$_3$

(b) Deformation of the cell followed by the polarization

(a) Oxygen sublattice

(b) Titanium sublattice

Mutual displacement of Ti and O sublatticities is followed by formation of an electric dipole and polarization of the crystal where $q$ is the charge, $x$ is displacement, $V_c$ is volume of the crystal cell

$$P = \frac{q \cdot x}{V_c}$$
**Ferroelectric Technology: Films to Devices to a Space Experiment**

**Modified 615 Element Scanning Ferroelectric Reflectarray: 2005-2009**
Prototype antenna with practical low-power controller assembled and installed in NASA GRC far-field range for testing. Low-cost, high-efficiency alternative to conventional phased arrays.

**First Ku-Band tunable Oscillator based on thin ferroelectric films**

**Practical Phase Shifters: 2003-2004**
Novel phased array concept based on quasi-optical feed and low-loss ferroelectric phase shifters refined. 50 wafers of Ba$_{0.5}$Sr$_{0.5}$TiO$_3$ on lanthanum aluminate processed to yield over 1000 ferroelectric K-band phase shifters. Radiation tests show devices inherently rad hard in addition to other advantages over GaAs.

**Cellular Reflectarray: 2010**
Derivative attracts attention for commercial next generation DirecTV, etc. applications.

**MISSE-8 Space Experiment: 2010**
Launched STS-134 includes 8 active Ba$_x$Sr$_{1-x}$TiO Ka-band phase shifters.

**Fundamental Research: 2000-2003**
Agile microwave circuits are developed [using room temperature Barium Strontium Titanate (Ba$_{0.5}$Sr$_{0.5}$TiO$_3$)], including oscillators, filters, antenna elements, etc., that rival or even outperform their semiconductor counterparts at frequencies up to Ka-band.

**Seedling Idea: 1997-1999**
Basic experiments with strontium titanate at cryogenic temperatures suggest loss tangent of ferroelectric films may be manageable for microwave applications.
Statistical Analysis of 48 PLD Ba_{50}Sr_{50}TiO_{3} Films on LaAlO_{3}

- 48 BSTO (50:50)/LaAlO_{3} wafers from Neocera, Inc. were RF characterized using a novel on-wafer probe technique and compared to high resolution XRD and ellipsometric data.

- The performance uniformity in terms of Q, phase shift and peak dielectric constant was excellent. $Q=14.1, \sigma =1.0; \varepsilon =2129, \sigma=149$, Average phase/element=20.5°, $\sigma =1.4°$.

Summary of full width, half maximum measurements of the (002) BST peak, for films deposited at different times.
**Coupled Microstripline Ferroelectric Phase Shifter in $S_{21}$ Configuration**

**Ferroelectric Phase Shifter Element (1 of 4)**

- Radial Stub Bias Tee
- Laser Ablated Ba$_{50}$Sr$_{50}$TiO$_3$ 0.35 $\mu$m film
- Cr-Au, 2 $\mu$m

**Magnesium Oxide Substrate (500 $\mu$m Thick)**

- 180 degrees total phase shift at 350 volts bias
- 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”
Photograph of prototype X-band phase shifter with 4 coupled microstripline sections and Si diode switch, which produced \( \approx 310^\circ \) of phase shift with 2.5 dB insertion loss.
EM Simulation of Hybrid X-band Phase Shifter

Insertion loss (Top - left axis) and insertion phase (Top - right axis) for SPST switch open and corresponding impedance data. Average Loss=2.5 dB

Insertion loss (Top - left axis) and insertion phase (Top - right axis) for SPST switch short and corresponding impedance data. Average Loss=2.3 dB
Hybrid X-Band Ferroelectric Phase Shifter
Measured Results with Wire-Bond Switch
Hybrid X-Band Ferroelectric Phase Shifter
Measured Results with Beam-Lead Si Diode Switch

Diode “On”
Hybrid X-Band Ferroelectric Phase Shifter
Measured Results with Beam-Lead Si Diode Switch

Diode “Off”
Typical Coupled Microstripline (Baseline)
Ferroelectric Phase Shifter in Reflection Mode

Au/Ag/Ti/Bo.5Sr.5TiO3/LaAlO3
Neocera Wafer 25 (no anneal), T = 300 K, 18.83 GHz
3 $\lambda$ 25 $\Omega$ Au/SrTiO$_3$/LaAlO$_3$ Tunable Ring Resonator

Figure 2.—$|S_{21}|$ of the side-coupled Au/SrTiO$_3$/LaAlO$_3$ resonator as a function of bias. The voltages correspond to the dc bias on the ring ($V_R$) and microstrip line ($V_L$).

Figure 1. Microstrip side-coupled ring resonator. $W = 406$ $\mu$m for the 25 $\Omega$ ring and 89 $\mu$m for the 50 $\Omega$ ring. $w = 89$ $\mu$m and $g = 25$ $\mu$m, $r = 1694$ $\mu$m.
A Side-Coupled Au/SrTiO$_3$ 3$\lambda$ Ring Resonator Provided Over 500 MHz Tuning at Ku-Band. The Laser Ablated Ferroelectric Film was 2 $\mu$m Thick. Bias was between 0 and 250 V.

**Reflectarray Concept**

Reflectarray surface contains many individual antenna elements, each integrated with a phase shifter.

Measured 19 GHz radar cross section of a 208 element passive reflectarray constructed on 0.79 mm thick substrate with $\varepsilon_r=2.2$.
615 Element K-band Reflectarray and Low Power Controller

Prototype Ferroelectric Reflectarray, Custom Power Supply and Controller in GRC Far-Field Antenna Range

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](image)

- **Name: C2**
  - Simulated curve with antenna
  - $\theta=45$ degree, $\phi=22.4$ degree
  - Without phase error

- **Name: C1**
  - Calculated curve with antenna
  - $\theta=45$ degree, $\phi=22.4$ degree
  - Without phase error

- **Name: C3**
  - Simulated curve with antenna
  - $\theta=45$ degree, $\phi=22.4$ degree
  - With phase error

- **Name: A2**
  - Simulated curve without antenna
  - $\theta=\phi=0$
  - Without phase error

- **Name: B2**
  - Simulated curve with antenna
  - $\theta=\phi=0$
  - Without phase error

- **Name: B3**
  - Simulated curve with antenna
  - $\theta=\phi=0$
  - With phase error

- **Name: B1**
  - Calculated curve with antenna
  - $\theta=\phi=0$
  - Without phase error

- **Name: A1**
  - Calculated curve without antenna

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**BPSK Modulation**
- $R_b=1.325$ Gbps
- $R_s=1.325$ Gsps
Radiation Testing at the University of Indiana Cyclotron Facility
Total Dose Radiation Tests
Effect on Loss

Data @ 19 GHz, Wafer # 24

AVERAGE LOSS=5.58 dB
Average Loss @ 0 Field=8.46 dB

13 Pristine Devices from Wafer 24

AVERAGE LOSS=5.62 dB
Average Loss @ 0 Field=7.47 dB

Same devices after exposure to 197 MeV protons (at target). Total fluence=9.9486x10⁹/cm² *

*Equivalent to 10 years in the International Space Station Hab Module
Total Dose Radiation Tests
Effect on Phase

13 Pristine Devices from Wafer 24
*Equivalent to 10 years in the International Space Station Hab Module

Same devices after exposure to 197 MeV protons (at target). Total fluence=9.9486x10^9/cm^2
*
Experiment Objective

The objective of the “reflectarray” experiment package is to characterize performance of critical components associated with the reflectarray antenna system as a prelude to a fully functional reflectarray space experiment. The operational scenario of MISSE-8, assuming a nadir facing ExPA mount, is similar to an operational scenario involving direct downlink from a LEO spacecraft.

1. Evaluate performance of FPGA 128 channel based high-voltage controller board. Rad Hard FPGA available from Actel. Supertex amplifiers/sample & hold are COTS.

2. Characterize on-orbit performance of phase shifters based on thin “ferroelectric” films. Evaluate effect of temperature cycling and long term effects of LEO radiation and AO, etc. exposure.

3. Employ lessons learned to develop a complete reflectarray antenna system and plan space experiment follow-on to execute actual communications link.
Ferroelectric Reflectarray Critical Components Experiment
Flight Hardware Concept

Engineering Model 128 channel High Voltage Controller Board

27.0 GHz internally referenced oscillator delay line

Passive Low Pass Filter

DC Proportional To Phase Shift (to power Interface Board)

27.0 GHz internally referenced oscillator delay line

SP8T switch module (typical)

≤ 300 Vdc across electrodes to bias ferroelectric films (8 devices)

RF section to interrogate ferroelectric phase shifters

Array Temperature Sensor (to power Interface Board)

Power/Interface Board

To CIB
Delivered “Ferroelectric Reflectarray Critical Components” MISSE-8 experiment hardware to NRL (overall system integrator) in February, 2010

**Experiment Objective:**

- To characterize long duration on-orbit performance of critical components of a reflectarray antenna system as a prelude to a fully functional reflectarray space experiment.
- Set the stage for a follow on science experiment to investigate the relationship between 1/f noise and gravity

**Reflectarray Benefits:**

- Combines best features of a gimbaled dish and a phased array
  - Dishes pose reliability risks (e.g. dust exposure) and limited slew rates
  - Phase arrays are expensive and inefficient
- 10-100x cost reduction to phased array
- Low power
- Large aperture size (not gain limited)
- Cooling not an issue
- High reliability- no moving parts
- Reciprocal surface- transmit & receive on same surface

**Flight:**

STS-134, Endeavor, May 16, 2011

**PI:**

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ISS Radiation Environment

- ISS environment is suitable for an SEE experiment
  - High inclination (51.5°) exposes ISS to higher fluences of trapped electrons and protons and solar and galactic cosmic rays than would be the case in a lower inclination orbit with the same altitude range, largely as a result of the overall shape and magnitude of the geomagnetic field
  - ISS passes through the South Atlantic Anomaly (SAA)

![Graph showing typical performance telemetry](graph.png)

Typical performance telemetry
Ferroelectric Reflectarray Critical Components Experiment (F-Recce)

Mission Specialist Drew Feustel with MISSE-8 on the outside of the International Space Station. Photo credit: NASA

F-Recce was developed by NASA's Glenn Research Center in Cleveland, Ohio, to accelerate mission insertion opportunities for a new type of “phased-array” antenna - an antenna that can redirect its main beam without physically repositioning itself. Conventional parabolic reflectors require a sophisticated mechanized gimbal system to steer the beam. This can be a prohibitively slow process plus all mechanical systems in space potentially suffer reliability problems because of the harsh environment. F-Recce will characterize critical components associated with NASA Glenn's reflectarray antenna system, including NASA Glenn invented thin film ferroelectric phase shifters, as a prelude to a fully functional space demonstration in a Low Earth Orbiting environment. Applications include: inter-satellite communications links, space-based radar/precipitation radar, docking and rendezvous, landing terrain radar, automotive collision avoidance radar, and others. The conditions of space are harsh and it is not easy to reproduce the combined environments to measure the effects of particle radiation, atomic oxygen, thermal cycling and ultraviolet conditions in labs.
Reflectarray Power Supply

Multilayer Piezoelectric Transformer

Proof-of-Concept Driver Circuit
Explore the Potential of a Piezoelectric Transformer as a Replacement for the Magnetic Transformer in an AC/DC Converter to Drive Ferroelectric Phase Shifters

The piezoelectric transformer is a high-Q system and is frequency, temperature, and load dependent.

Two approaches to driving the circuit were used: the first was fixing the drive frequency at the resonant frequency of 54.7 kHz and varying the input to achieve desired output voltages, and the second was fixing the input voltage to the minimum necessary for reaching the 300 VDC and sweeping the frequency.

\[
\frac{V_o}{V_i} = \frac{s R_L C}{s^3 n^2 R_L C_0 L C + s^2 (n^2 R_L C_0 C R + n^2 L C) + s (n^2 R_L C_0 + n^2 C R + C R_L) + n^2}
\]

Cross Sectional TEM of a heterostructure consisting of 80 nm (ZrO$_2$)$_{0.91}$(Y$_2$O$_3$)$_{0.09}$/200 nm Bi$_4$Ti$_3$O$_{12}$/375 nm Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ films on 100 Si

A thin interfacial layer is present at the YSZ-BTO interface. The BTO-BSTO interface appears abrupt.
Measured Reflection Coefficient of $\text{Ba}_{50}\text{Sr}_{50}\text{TiO}_3$/Si Patch
Residual cryogenic phase noise measurement system. The HP 70420 system contains the phase detector electronics and quadrature was achieved by slightly detuning the synthesizer frequency.

Phase noise profile of a nominally 350 nm $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ film with a 15.8 GHz carrier at $T=290$ K. Bias across the interdigital structure is varied from 0 to 100 V in steps of 25 V.

Phase noise profile of a nominally 350 nm $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ film with a 15.8 GHz carrier at $T=140$ K. Bias across the interdigital structure is varied from 0 to 100 V in steps of 25 V.
Possible Magnetoresistive Effect from \( \text{Bi}_4\text{Ti}_3\text{O}_{12}/375 \text{ nm} \) \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3 \) films on (001) Si (Sample Arranged in a van der Pauw Configuration)
Conclusions

• Tunable microwave components, based on thin ferroelectric films, have been developed that rival the performance of, or even outperform, their semiconductor counterparts

• Ba$_x$Sr$_{1-x}$TiO$_3$ films appear to be robust enough for space applications

• Thin ferroelectric film technology may enable new types of agile microwave components

• Low loss phase shifters based on ferroelectric films may enable new types of phased array antenna architectures

• The magnetoelectric effect – the induction of polarization by a magnetic field – was first postulated by Curie in 1894. Further evidence was presented here.

• Applications of ferroelectric films on semiconductor substrates is a largely unexplored area

• Ba$_x$Sr$_{1-x}$TiO$_3$ is one of hundreds of potentially superior perovskite and non-perovskite based ferroelectric materials yet to be explored