Optimization of Thin Film ferroelectrics for Communication Applications

Abstract

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The application of thin film ferroelectrics for the development of tunable microwave components have been a very active field of investigation throughout the last decade. This presentation will provide an overview of some of the activities in the aforementioned area by other research groups and the current status of the field. In particular, we will discuss the efforts currently underway at the NASA Glenn Research Center in the area of phase shifter development using $Ba_xSr_{1-x}TiO_3$ ferroelectric thin films. Emphasis will be given to the approaches that have been investigated in order to improve the performance (i.e., figure of merit) of these devices. Some of these approaches deal with the details of circuit design parameters, while others are related to the optimization of material properties through different deposition techniques. Experimental results and discussions on the aforementioned topics will be presented.

Optimization of Thin Film Ferroelectrics for Communications Applications

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Collaborators

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Outline

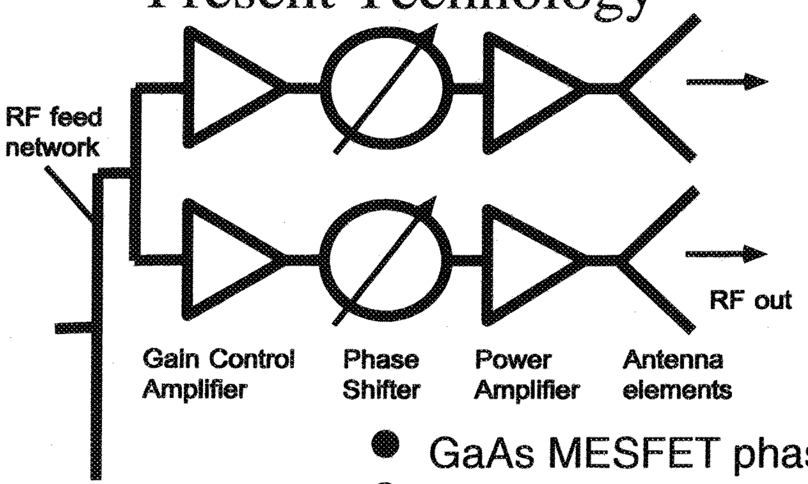
- Ferroelectrics
- Experiments
- Results
- Conclusions

Why Ferroelectrics?

- High versatility: dielectric properties of ferroelectrics can be controlled either electrically, thermally, or through material processing means.
- Consequently, FE-based electronic circuits with tunable features (e.g., frequency, phase, etc.) can be designed and fabricated.
- Tunable components, filters, oscillators, and phase shifters have been demonstrated and reported.
- Careful material preparation and selection, as well as appropriate circuit design are required for <u>advantageous</u> practical application.
- For communications applications, it is relevant that the above features translate into smaller, light-weight and highly reconfigurable systems. These demands are more stringent for space-based communication networks.

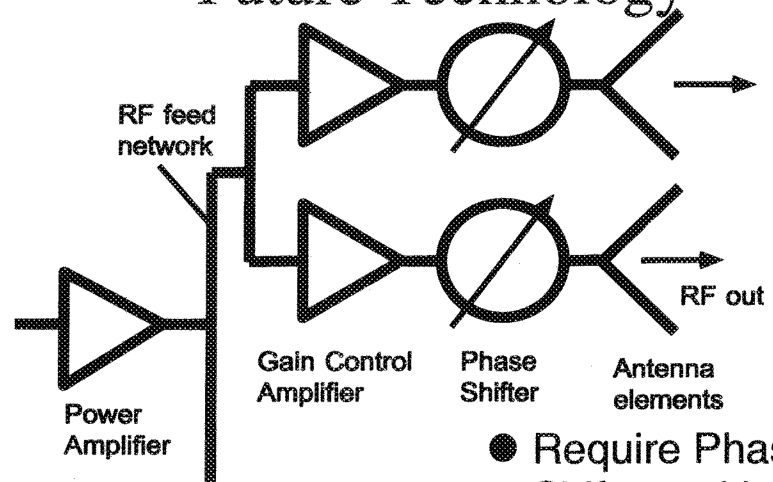
Present and Future Technology for Phased Array Antennas

Present Technology



- GaAs MESFET phase
- shifters have 6-12 dB
- insertion loss.

Future Technology



- Require Phase
- Shifters with low
- (e.g.,< 3 dB)
- insertion loss (e.g., MEMS, Ferroelectrics)

- Present phase array antennas use one phase shifter and amplifier chain for each aperture.
- If the phase shifter loss is reduced, a single power amplifier may feed several apertures without degrading system performance. Reduces MMIC part count, cost, size, and complexity.

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Examples of Thin Film Ferroelectrics Investigated

- $SrTiO_3$
- $Ba_{1-x}Sr_xTiO_3$
- $Sr_xBa_{1-x}Nb_2O_6$
- $(Pb)SrTiO_3$
- $(Pb,La)(Zr,Ti)O_3$

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Fabrication Techniques

- Pulsed Laser Deposition (PLD)
- Sol-gel
- Chemical Vapor Deposition (CVD)
- Metallorganic Chemical Liquid Deposition (MOCLD)
- Chemical Combustion Vapor Deposition (CCVD)
- Magnetron Sputtering
- Molecular Beam Epitaxy (MBE)

Tunable Components

Resonators

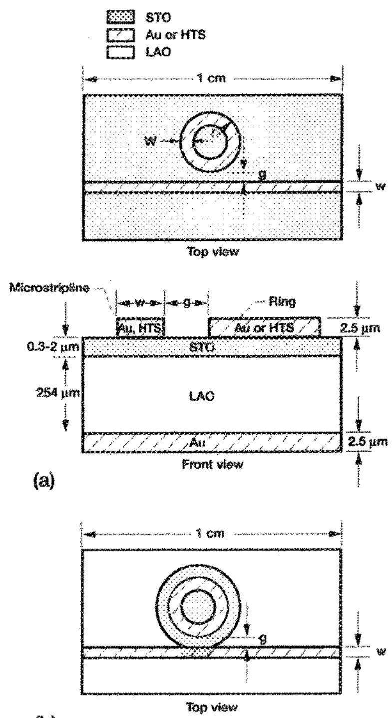


FIGURE 1 Microstripline side-coupled ring resonator. W = 406 μm for the 25 Ω ring and 89 μm for the 50 Ω ring. w = 89 μm and g = 25μm, r = 1694 μm.

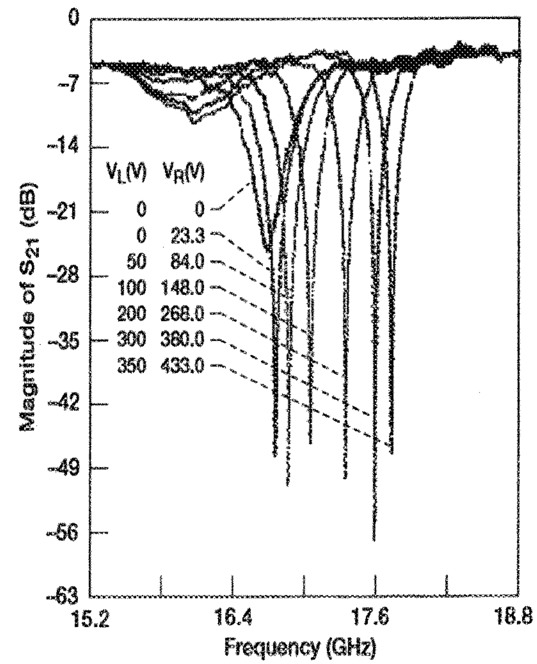
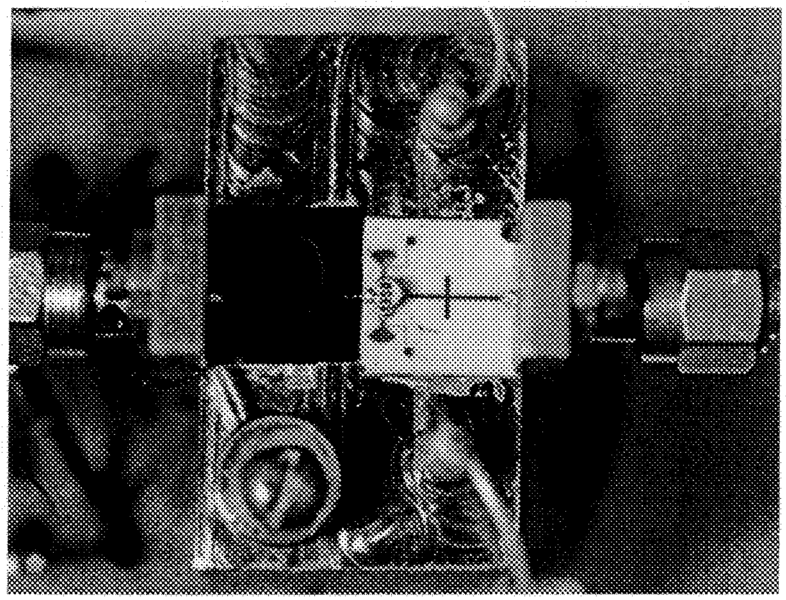


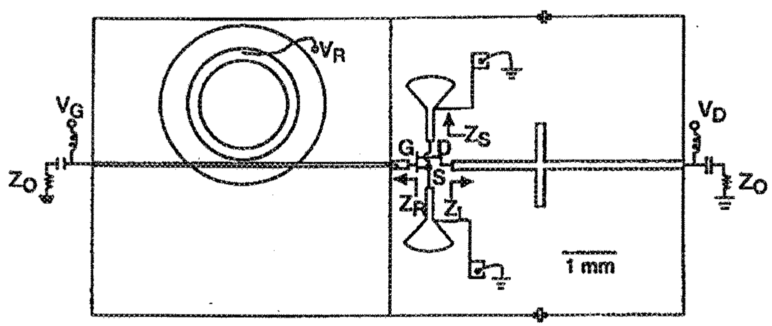
Figure 2.—$|S_{21}|$ of the side-coupled $Au/SrTiO_3/LaAlO_3$ resonator as a function of bias. The voltages correspond to the dc bias on the ring (V_R) and microstrip line (V_L).

Ref: F. W. Van Keuls, R. R. Romanofsky, D. Y. Bohman, and F. A. Miranda, INFLUENCE OF THE BIASING SCHEME ON THE PERFORMANCE OF Au/SrTiO3/LaAlO3 THIN FILM CONDUCTOR/FERROELECTRIC TUNABLE RING RESONATORS, Integrated Ferroelectrics, Vol. 22, p. 883 (1998).

Tunable Components

- **Oscillators**





First demonstration of a cryogenic tunable oscillator using both GaAs PHEMT and thin film ferroelectric technologies that operates in the microwave frequency range.

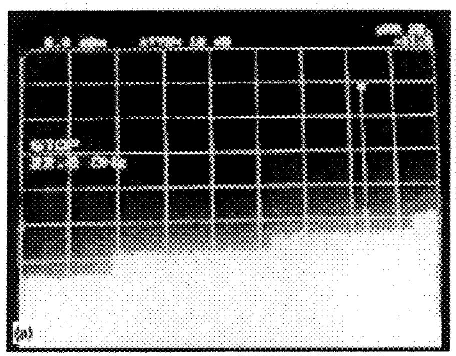
Ref: R. R. Romanofsky, F. W. Van Keuls, and F. A. Miranda, A CRYOGENIC GaAs PHEMT/FERROELECTRIC Ku-BAND TUNABLE OSCILLATOR, Journal de Physique IV, Vol. 8, p. 171 (1998).

Tunable Components

•Oscillators (cont)

Cryogenic GaAs PHEMT/Ferroelectric Ku-Band Tunable Oscillator

A Side-Coupled Au/SrTiO3 3λ Ring Resonator Provided Over 500 MHz Tuning at Ku-Band. The Laser Ablated Ferroelectric Film was 2 μm Thick. Bias was between 0 and 250 V.



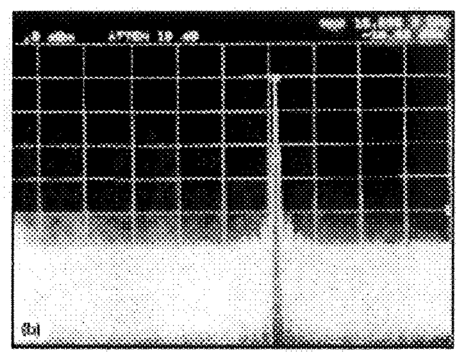


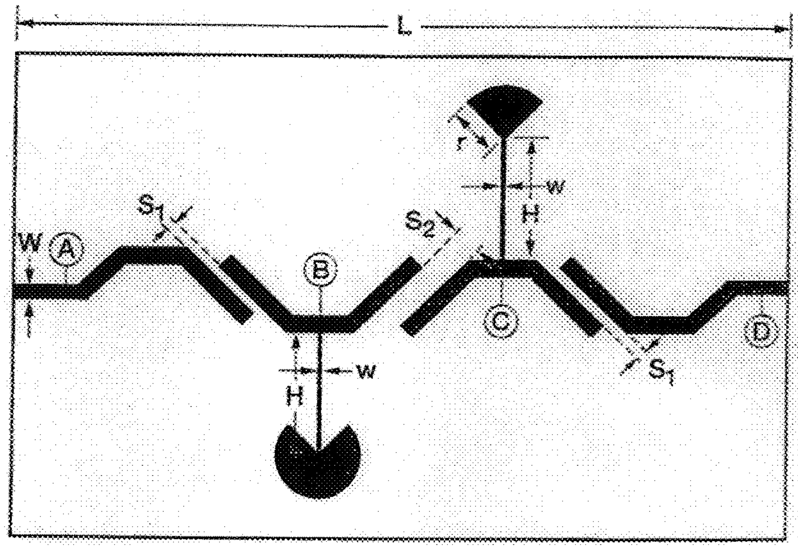
Figure 4.—VCO signals as measured on an HP 8566B Spectrum Analyzer at 43 K with V_d = 2.1 V, V_g = −0.2 V, I_d = 13.9 mA and Vring = 38 V. The scale on (a) is 2 to 22 GHz, and (b) shows a 500 MHz span with oscillation frequency at 16.696 MHz.

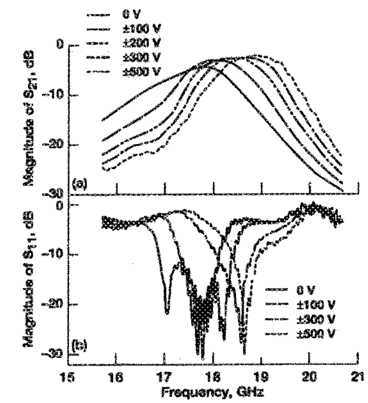
Ref: R. R. Romanofsky, F. W. van Keuls, and F. A. Miranda, A CRYOGENIC GaAs PHEMT/FERROELECTRIC Ku-BAND TUNABLE OSCILLATOR, Journal de Physique IV, Vol. 8, p. 171 (1998).

Tunable Components

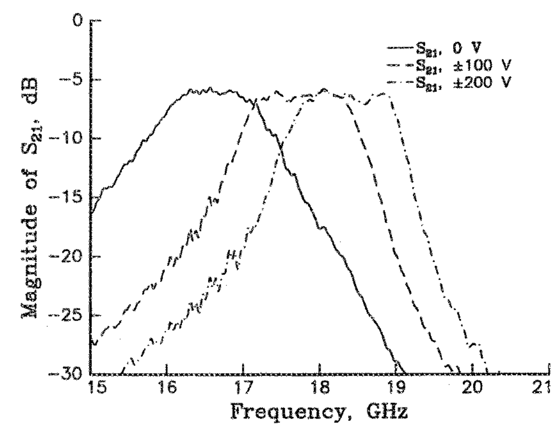
Filters

2-pole band pass filter





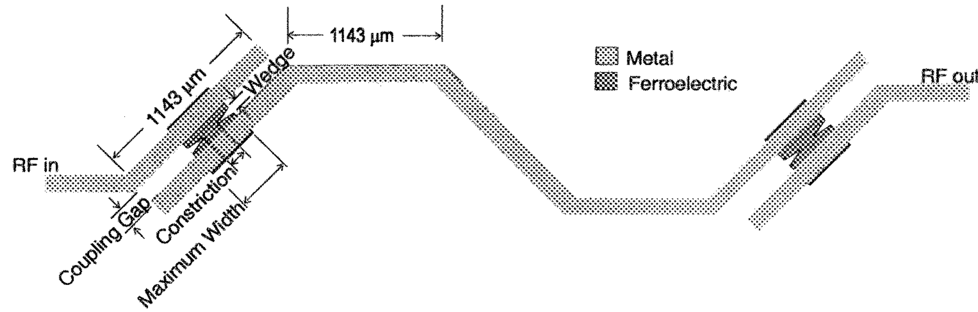
The swept frequency response of a tunable filter at 77K for bipolar bias voltages between 0 and ±500 V.



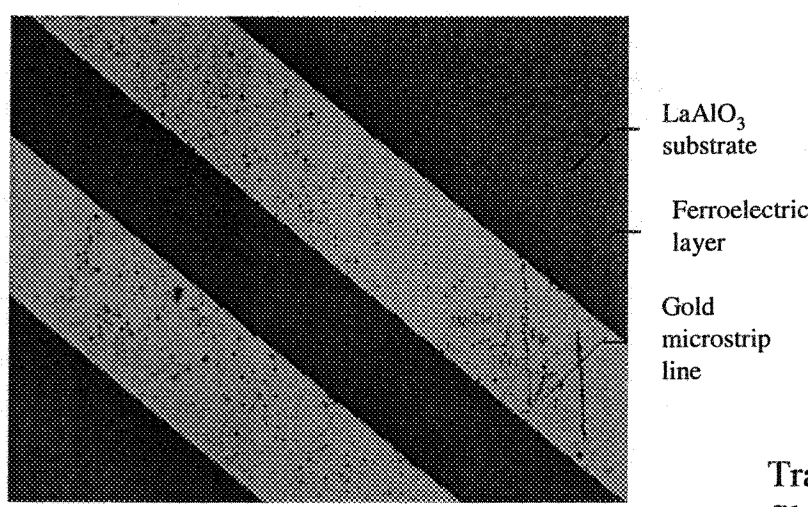
Ref: G. Subramanyam, F. W. Van Keuls, and F. A. Miranda, A NOVEL K-BAND TUNABLE MICROSTRIP BANDPASS FILTER USING A THIN FILM HTS/FEROELECTRIC/DIELECTRIC MULTILAYER CONFIGURATION, IEEE MTT-S International Microwave Symposium Digest, Vol 2, p. 1011 (1998).

Tunable Bandpass Filters Using Selectively Etched Ferroelectric Films

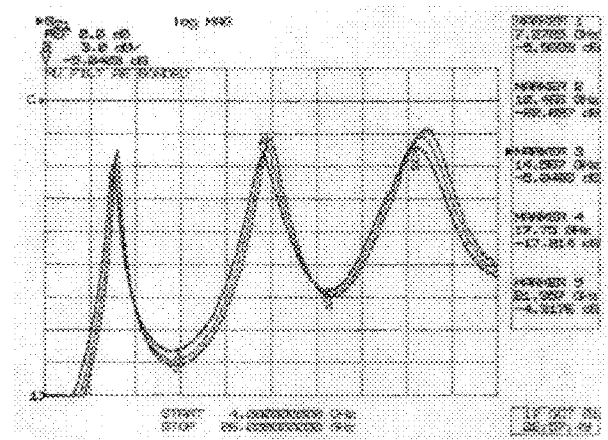
F. A. Miranda, C. H. Mueller, F. W. Van Keuls, G. Subramanyam, and S. Vignesparamoorthy,
PERFORMANCE ENHANCEMENT OF TUNABLE BANDPASS FILTERS USING SELECTEIVE ETCHED FERROELECTRIC THIN FILMS, Presented at the 13th International Symposium on Integrated Ferroelectrics, Nara, Japan, May 28-June 1, 2002.



Schematic of one-pole microstrip filter with etched ferroelectric layer



Photograph of coupled section of filter, showing etched ferroelectric layer



Transmission (S_{21}) versus frequency for selectively etched filter, at bias levels of 0, 200, and 400 volts. At ~21 GHz, the second harmonic was tunable by 528 MHz, and the insertion loss varied from 4.2 to 2.8 dB.

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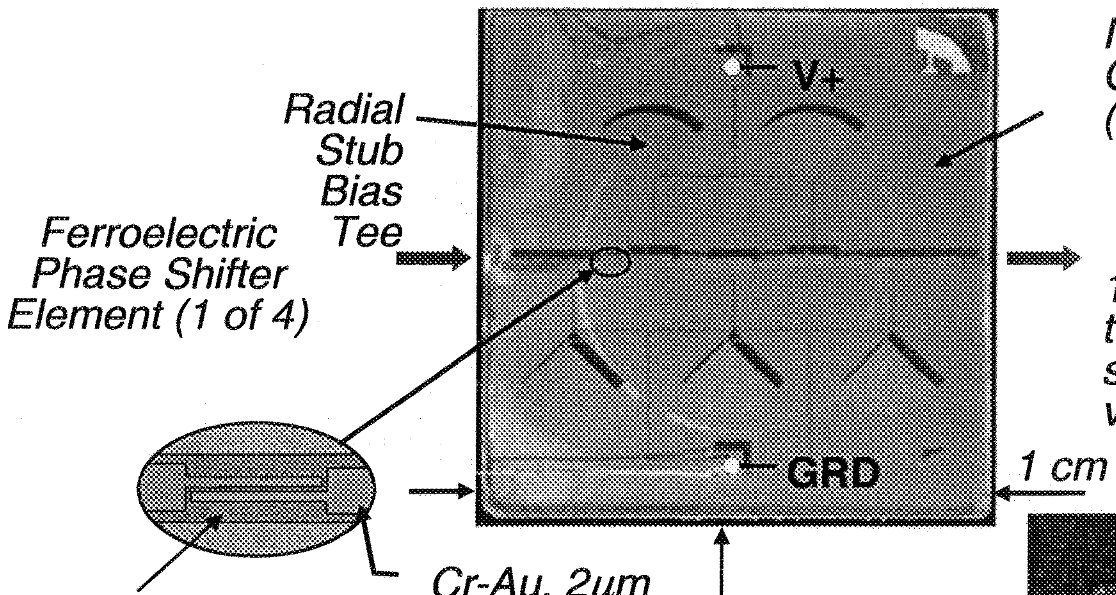
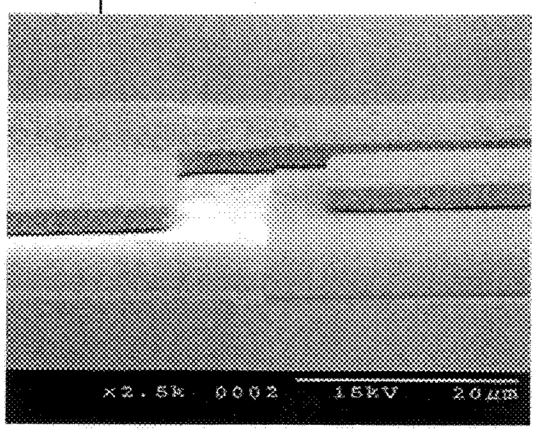
Coupled Microstripline Ferroelectric Phase Shifter in S_{21} Configuration

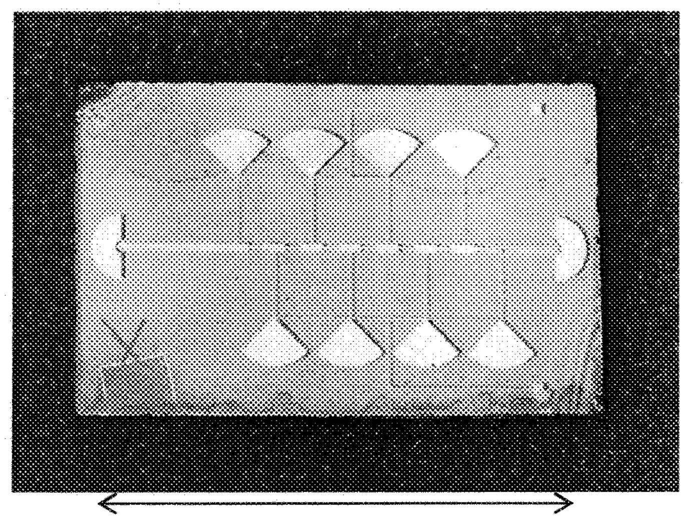


Laser Ablated $Ba_{50}Sr_{50}TiO_3$ 0.35 mm film

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



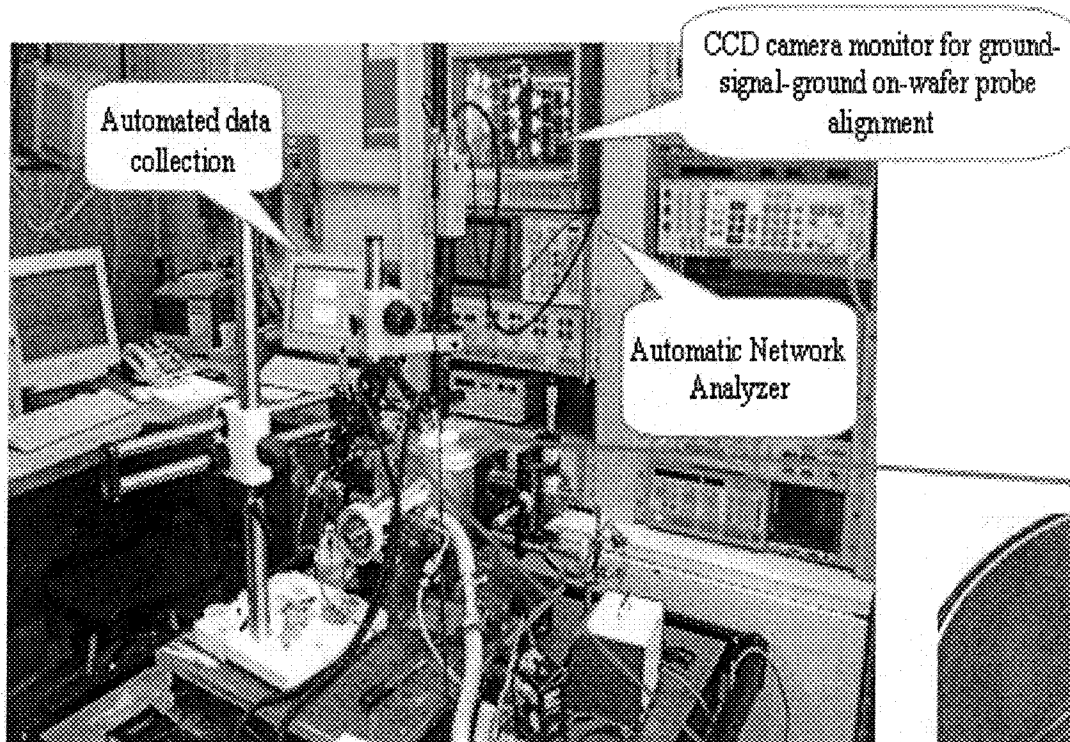
0.3 mm MgO with a ≈400 nm Laser Ablated $Ba_xSr_{1-x}TiO_3$ Film "Probe-able" phase shifter



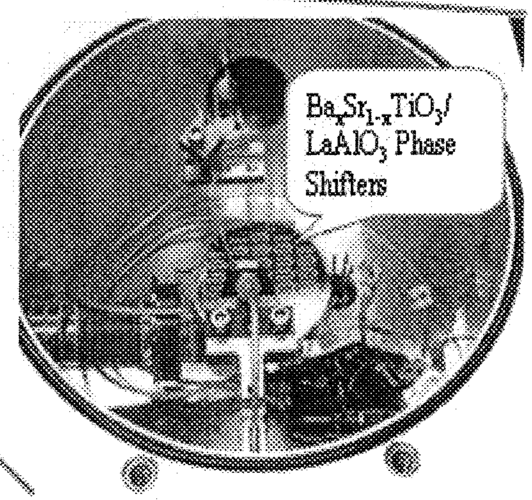
1.2 cm

"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

Customized On-Wafer Phase Shifter Characterization Set Up

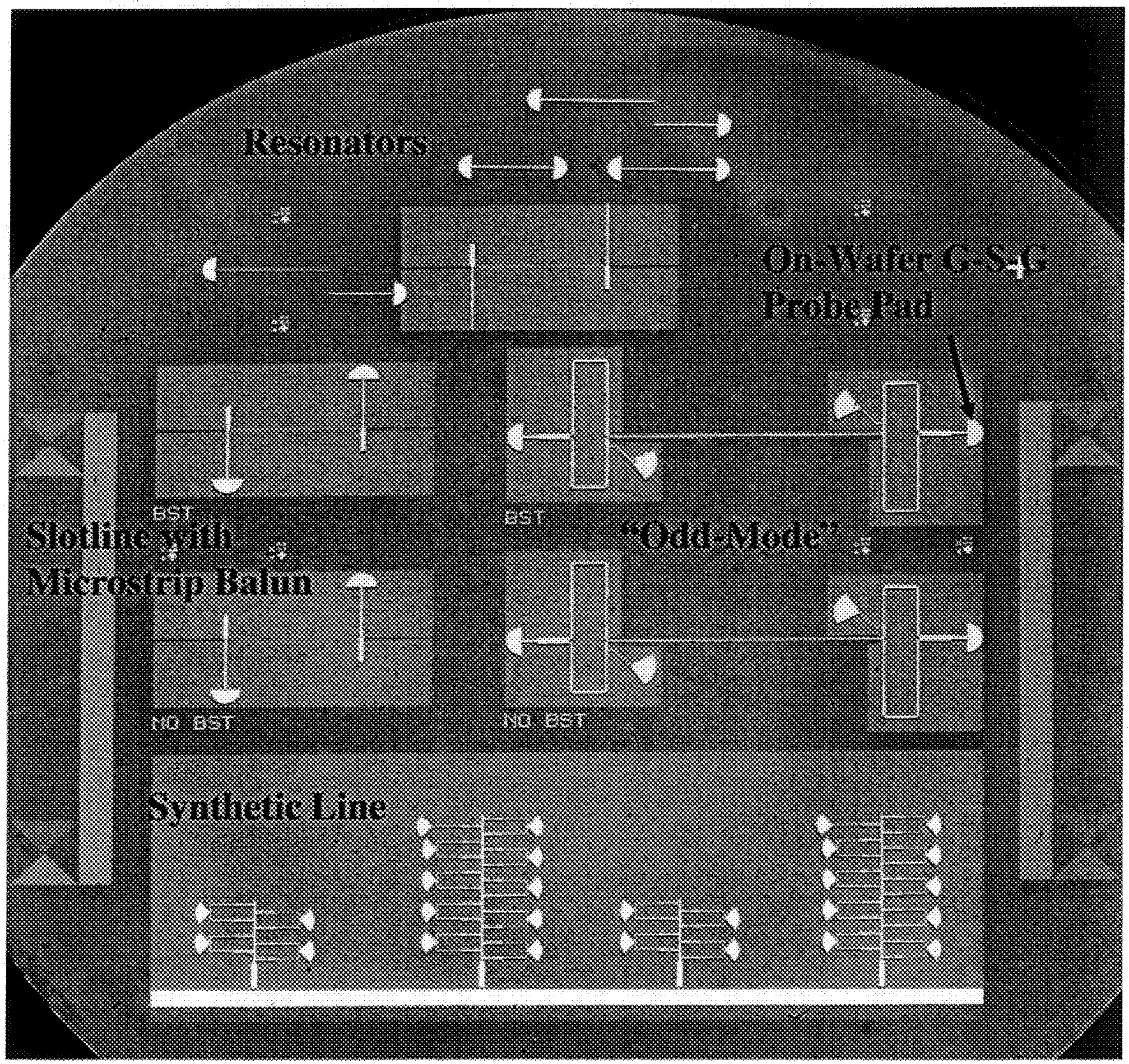


NASA GRC's semi-automated on-wafer probing system allows accurate characterization of ferroelectric phase shifters (S- through Ka-band.)

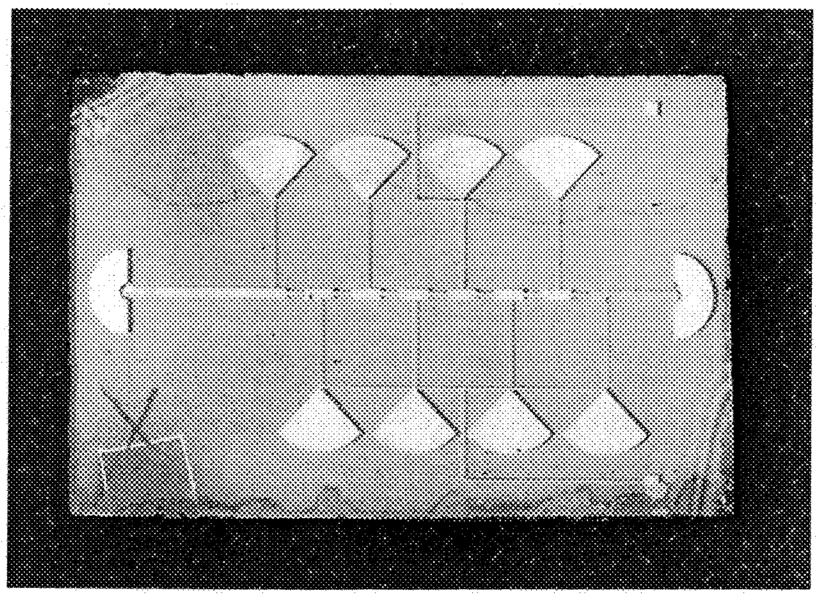


Probe Station Assembly

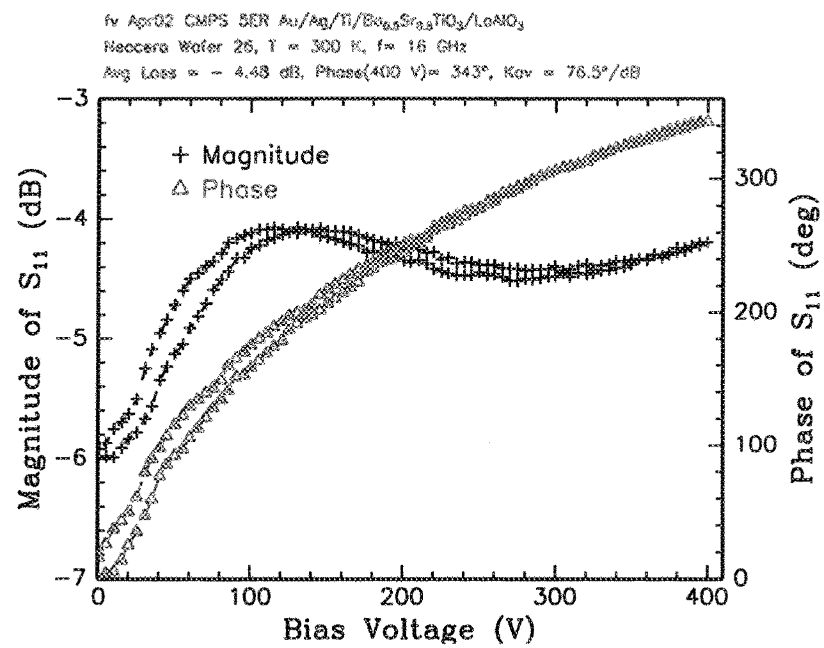
Various Transmission Line Thin Ferroelectric Film Phase Shifters



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



BSTO Thin Film Ferroelectric Phase Shifter on $LaAlO_3$



The average K value is about 75 degrees per dB.

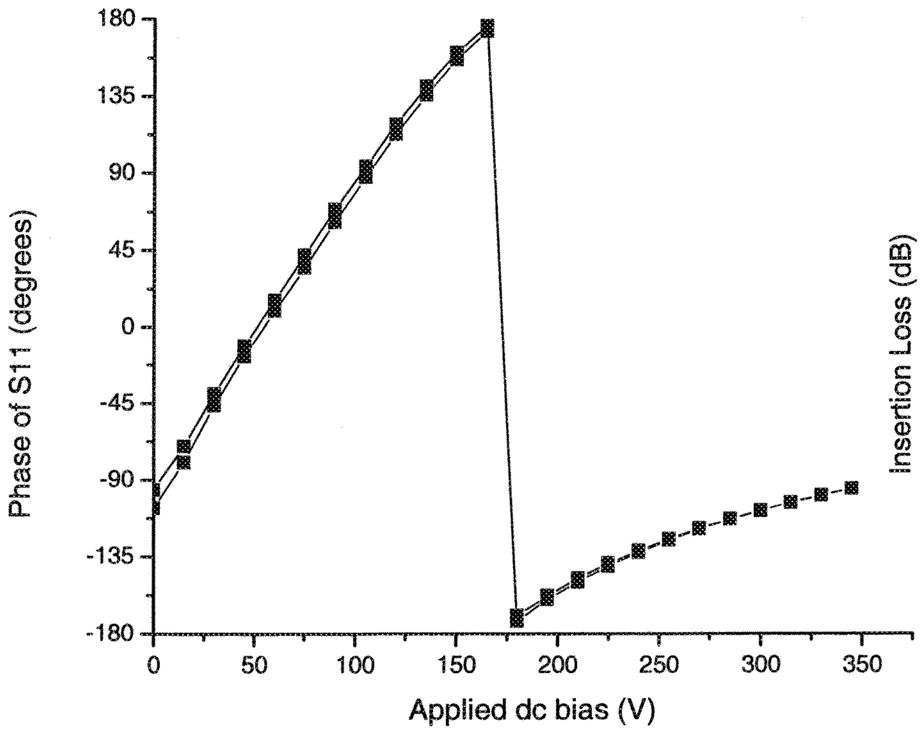
Comparison of some Ferroelectric-based Phase Shifters

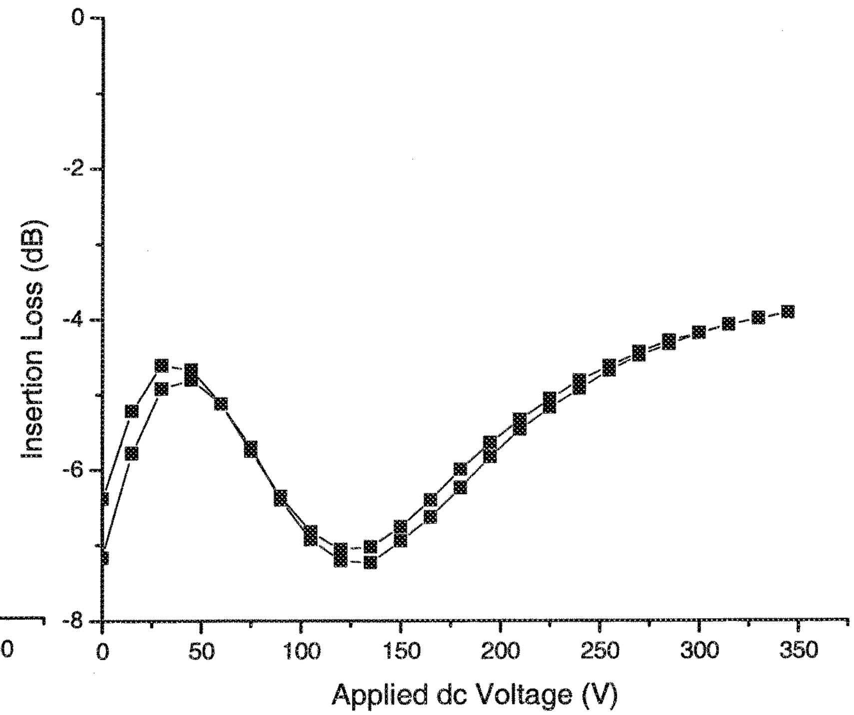
Group	Freq. (GHz)	Max Phase Shift (deg)	K (deg/dB)	Voltage / E field	Circuit	Comments
NASA Glenn Miranda et al.	19	430°	70	350 V / 46 V/μm	Coupled microstrips on top of BST	Narrowband, matching narrowband patches
UCSB York et al. (1)	10	240°	80	20 V / 71 V/μm	Parallel Plate BST varactors in a periodically loaded transmission line	Broadband but maximum phase shift proportional to frequency
Eltech Kozyrev et al. (2)	2.5 30 60	360° 360° 220°	95 40 22	350 V / ~35 V/μm	Cascaded and loaded line phase shifters	Narrowband

References for Comparison Table

1. Acikel et al., IEEE Micr. and Wireless Comp. Lett., 12, p.237-239 (2002).
2. Kozyrev et al., Integrated Ferroelectrics, 55, p. 838, p.847 (2003).

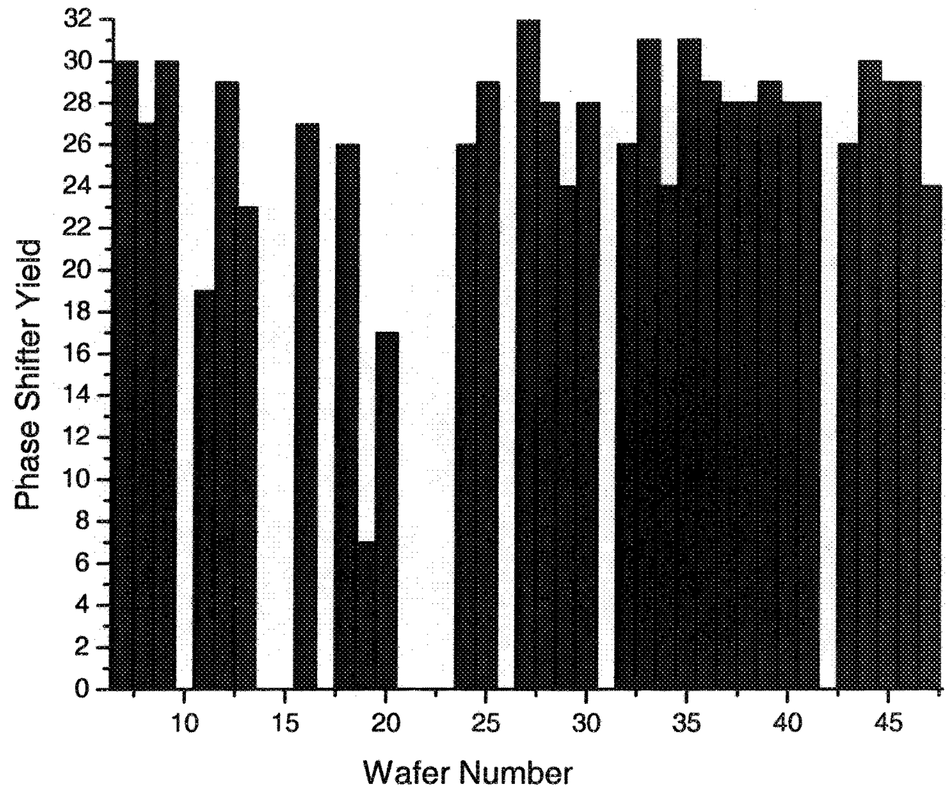
Coupled Microstrip Phase Shifter Performance





Operating at the array design frequency of 18.8 GHz, this phase shifter covers a full 360° phase shift. Insertion Loss varies from -4 to -7 dB

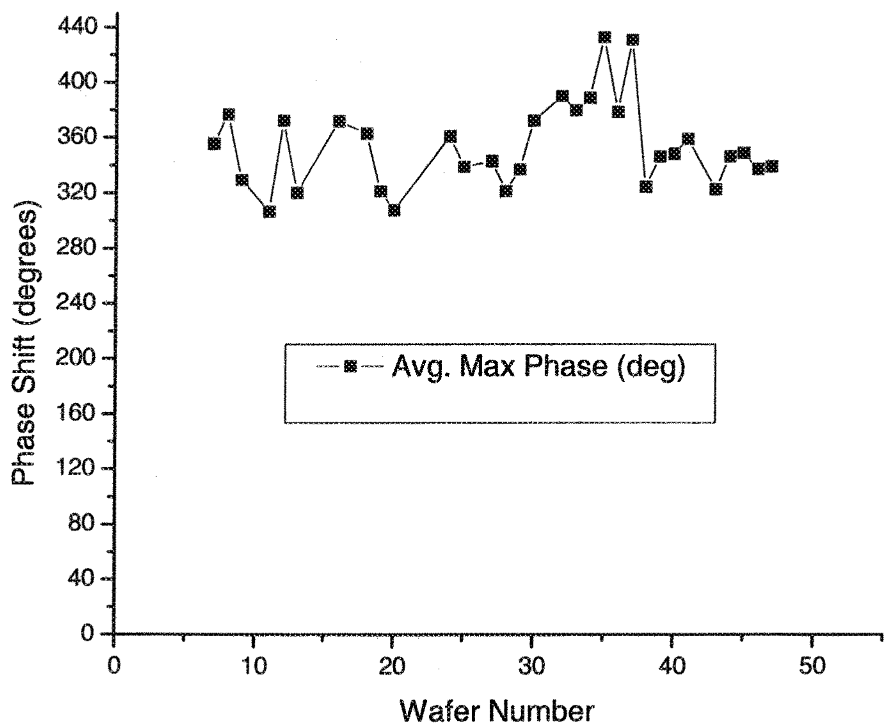
Measurements of 822 Phase Shifters

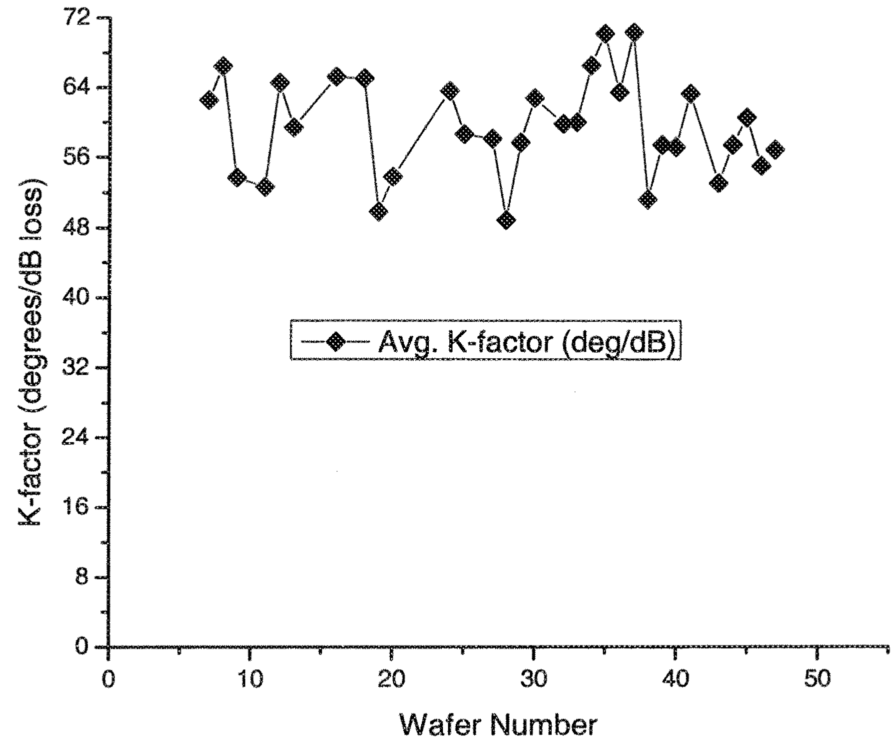


Number of Successful Phase Shifters out of 32 possible fabricated on each 2" diameter BST coated LaAlO3 (blank wafer numbers used for other purposes)

***Wafers 19 and 20 used in outsourced fabrication trials**

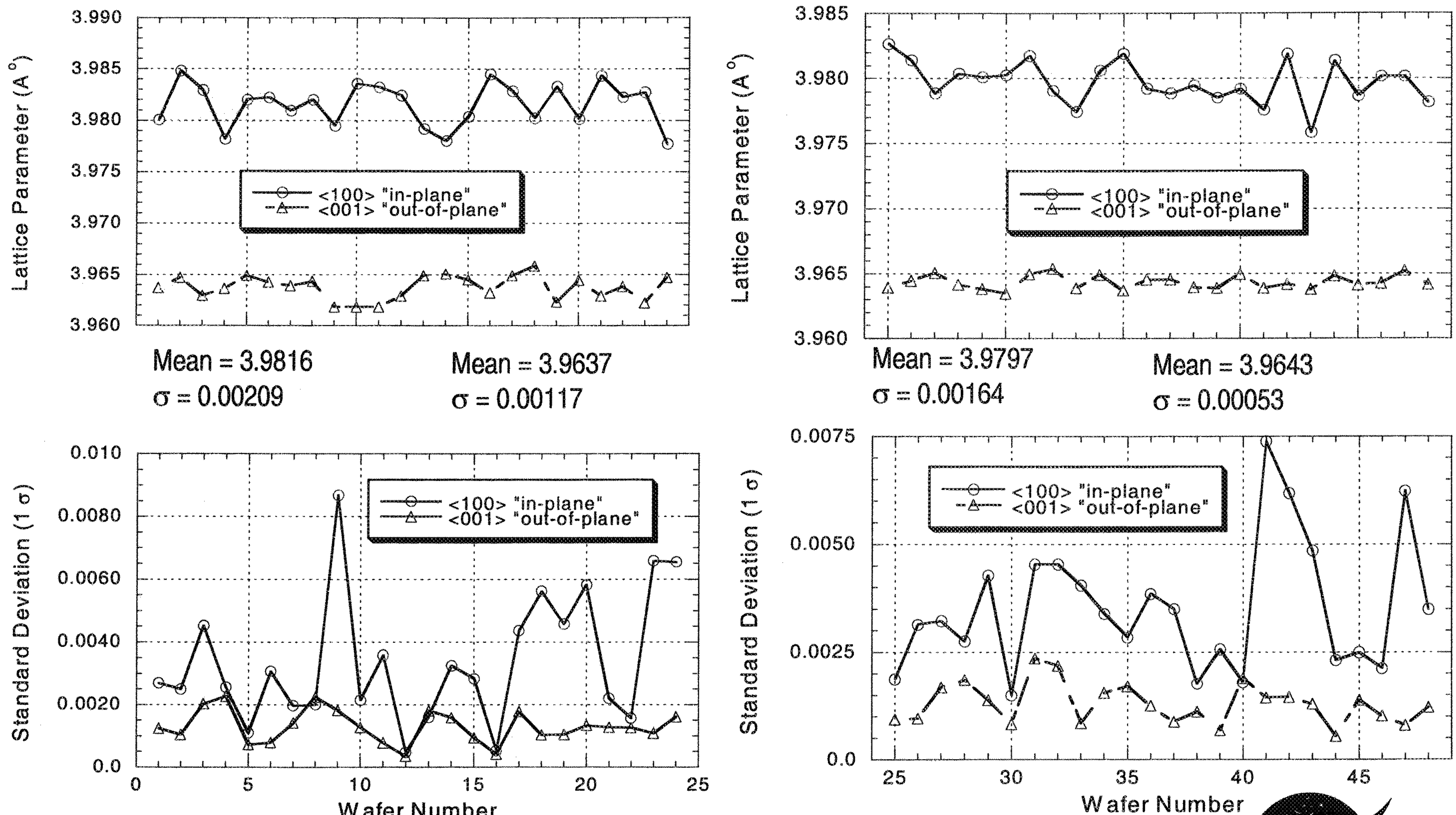
Phase Shifters for Array (continued)





Average Maximum Phase Shift and K-factor figure of merit for fabricated Phase shifters.

X-ray Diffraction Analysis



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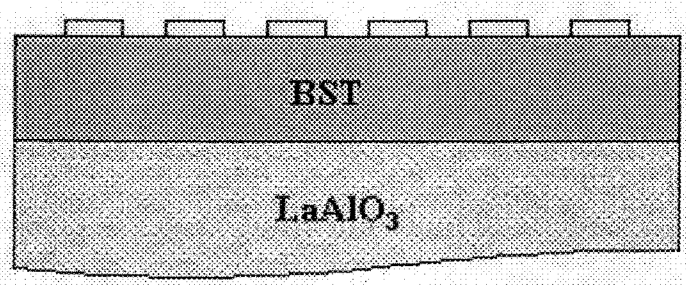
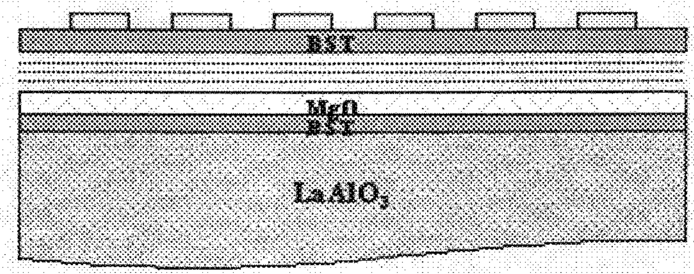
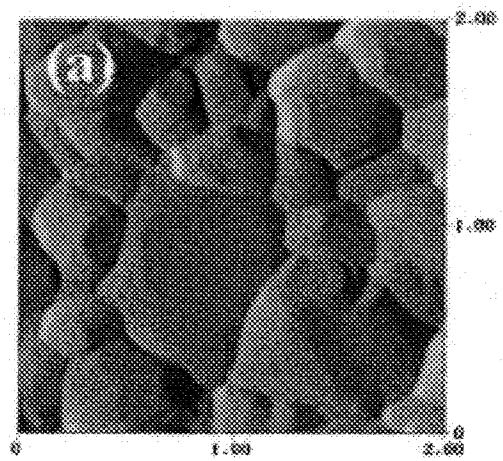
Improvement of Microwave Performance of Ferroelectric Thin Films via Cation Substitution*

*Collaboration with Dr. Ram Katiyar's group at the University of Puerto Rico, San Juan.

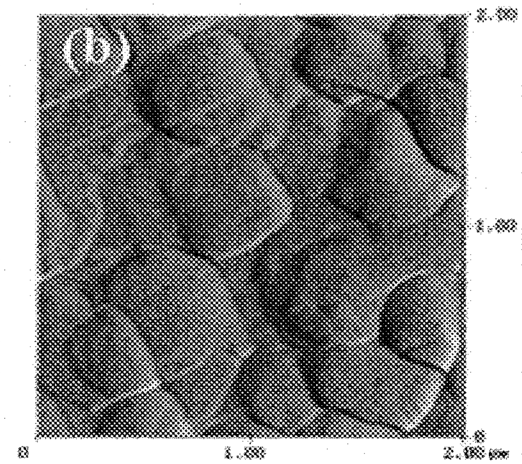
$Ba_{0.5}Sr_{0.5}TiO_3$:MgO Heterostructured films for tunable dielectric device applications







Pure BST



BST:MgO

Two Types of Films

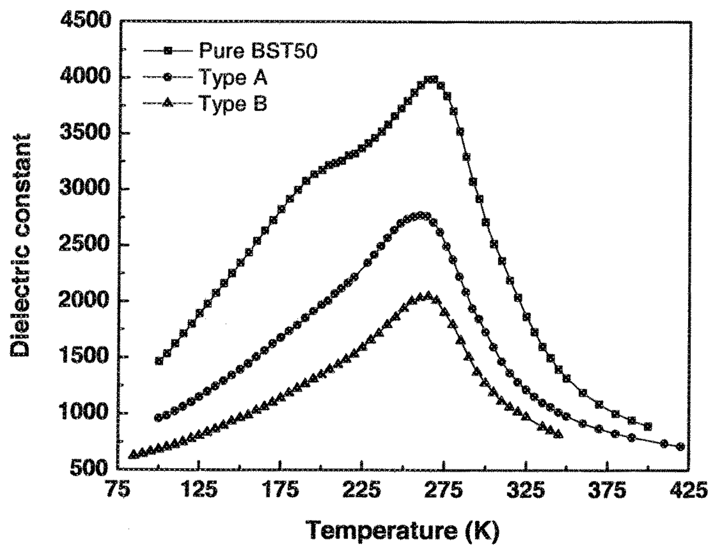
- Type A BSTO/MgO Films: Alternate BST(50:50) (~65 nm)/MgO(~40 nm) Layers with BSTO as the initial and final layer, that resulted in BST:MgO volume ratio of ~62:38.

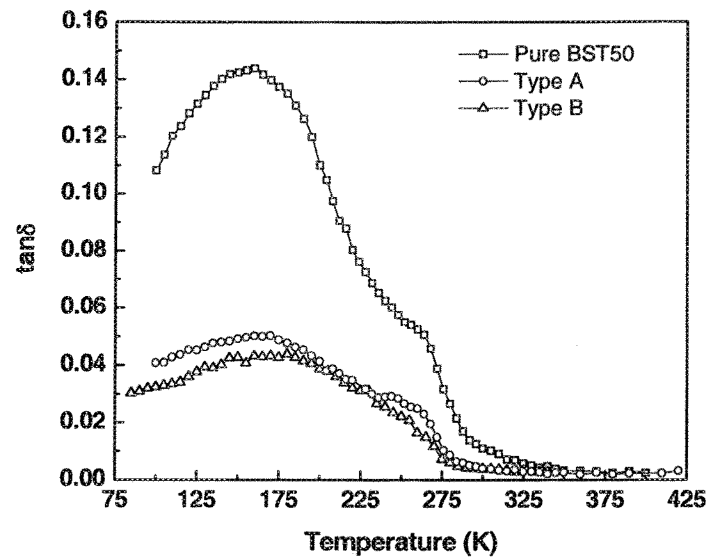
- Type B BSTO/MgO films: Prepared by coating alternating thick layers of BSTO(50:50) (~260 nm) and Mgo (~120 nm) with MgO as the first and BSTO as the terminating layer to get the BST:MgO volume ratio of ~ 68:32.

- Both types of films were deposited on $LaAlO_3$ and annealed at 1100°C for 6 hr.

- A gold planar capacitor structure consisting of 50 fingers each 7 mm long, 20 μm wide and with gaps of 15 μm was deposited to investigate the dielectric properties of the composite films at low frequencies.

Dielectric measurements @ 1MHz: Pure BST50 and BST:MgO thin films



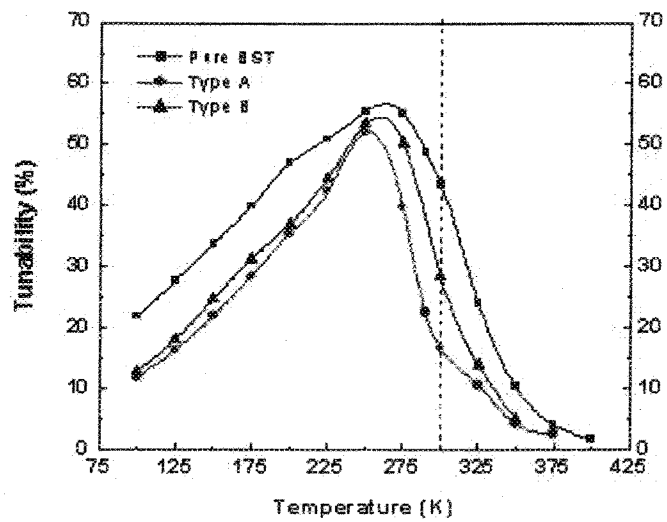


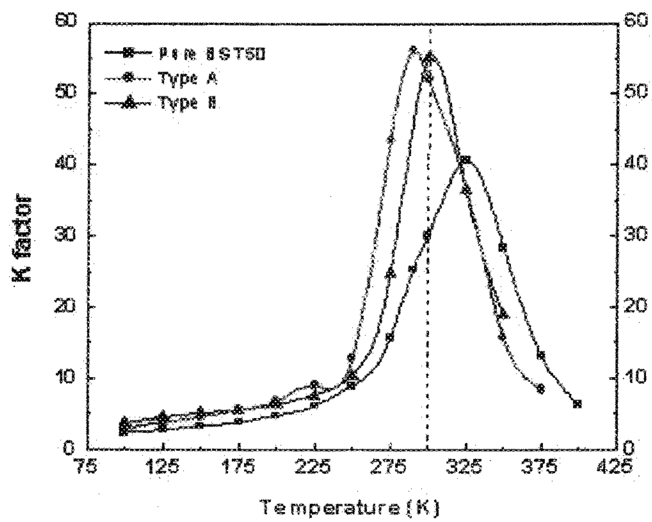
Note: second broad hump around 180 K in case of pure BSTO50 is due to the orthorhombic to tetragonal phase transition.

Film	Dielectric constant	tanδ	(%) Tunability @ 25.3 kV/cm	K-factor
Pure BST	2714	0.014	43.5	30.03
Type A	1729	0.003	16.7	52.2
Type B	1277	0.004	28.5	55.1

Magnesium additions improve the microwave Performance of BSTO thick and thin films

Tunability and K factor (@ 1 MHz)

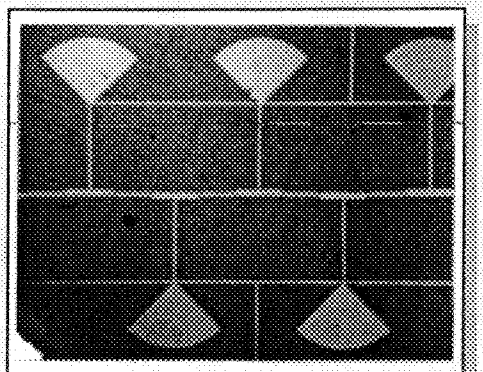




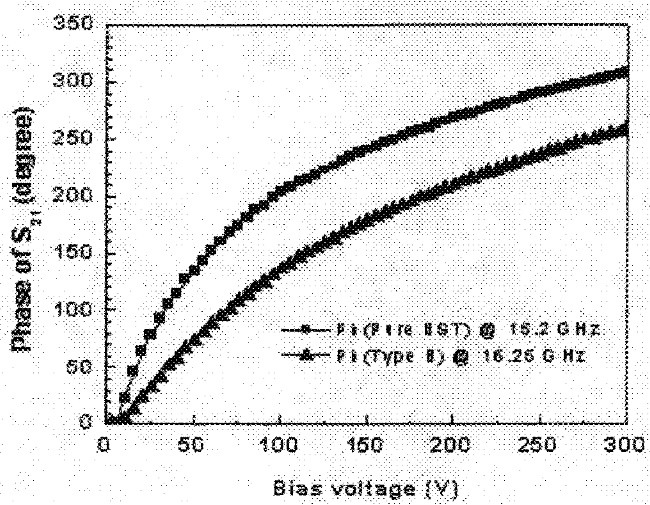
Film	Dielectric constant	tanδ	(%) Tunability @ 25.3 kV/cm	K-factor
Pure BST	2714	0.014	43.5	30.03
BST:MgO	1277	0.004	28.5	55.1

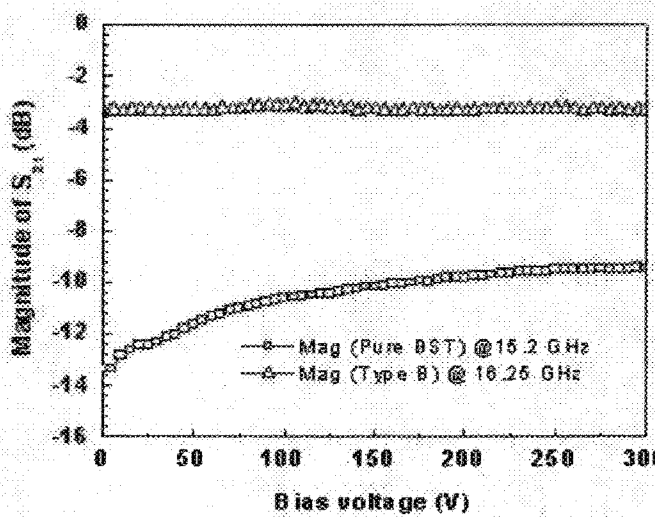
Magnesium additions improve the microwave Performance of BSTO thick and thin films

Fabrication of phase shifter (15-7 GHz)and results at 400 kV/cm



Film	κ-factor (^{0}/dB)
Pure BST	32.66
BST:MgO	78.66





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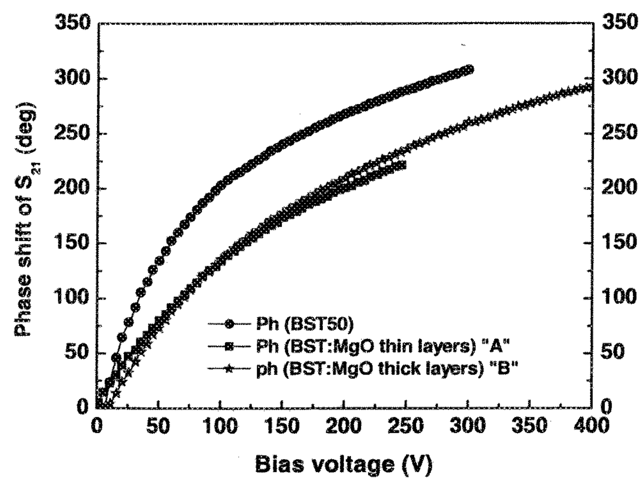
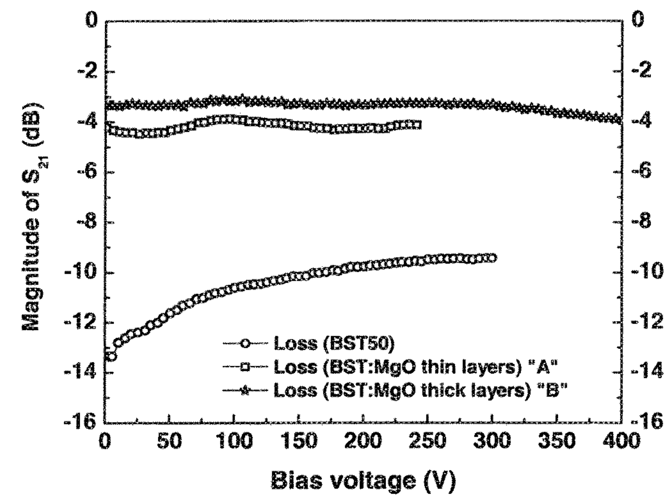
Pure BST50 and BST:MgO thin films for Phase shifter applications





Film	Frequency in GHz	Figure of merit, (°/dB)
Pure BST50	15.20	30.54 (333kV/cm)
BST:MgO "A"	13.50	62.26 (333kV/cm)
BST:MgO "B"	16.25	72.52 (333kV/cm), 89.30 (533 kV/cm)

- In Sol-gel derived BST50:MgO heterostructured film (Type A and B), losses reduced considerably as compared to pure BST50 film.
- By changing the sequence of MgO and BST50 layers (Type B), we were able to achieve better figure of merit of up to ~89 °/dB.

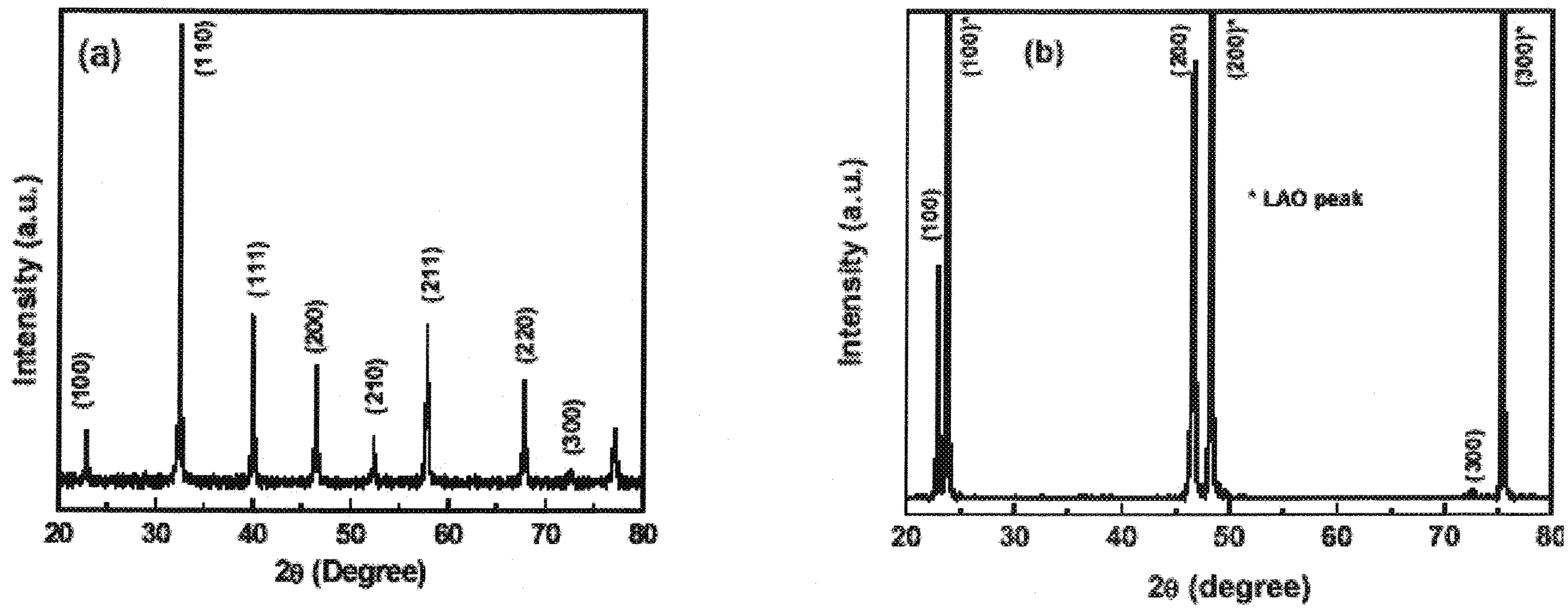
Magnesium additions improve the microwave Performance of BSTO thick and thin films

- Epitaxial quality of BST thin film is maintained when MgO is introduced.
- Dielectric characterization results exhibit that the loss tangent has been significantly reduced with MgO inclusion. Reduction in loss tangent has been attributed to the MgO solubility in BST and microstructural modifications induced by the MgO layers.
- High frequency measurements shows the significant reduction in the dielectric losses, hence increase in the effective figure of merit for the high frequency phase-shifters.

Lead Strontium Titanate ($Pb_xSr_{1-x}TiO_3$) Thin Films

- The PST system is of interest since it only have one phase transition ($x \leq 0.4$) compare to three for the BST system.
- $Pb_{0.3}Sr_{0.7}TiO_3$ films were deposited on $LaAlO_3$ by the sol-gel technique.
- XRD and AFM techniques were used to determine the structural and surface properties, respectively, of the PST films.

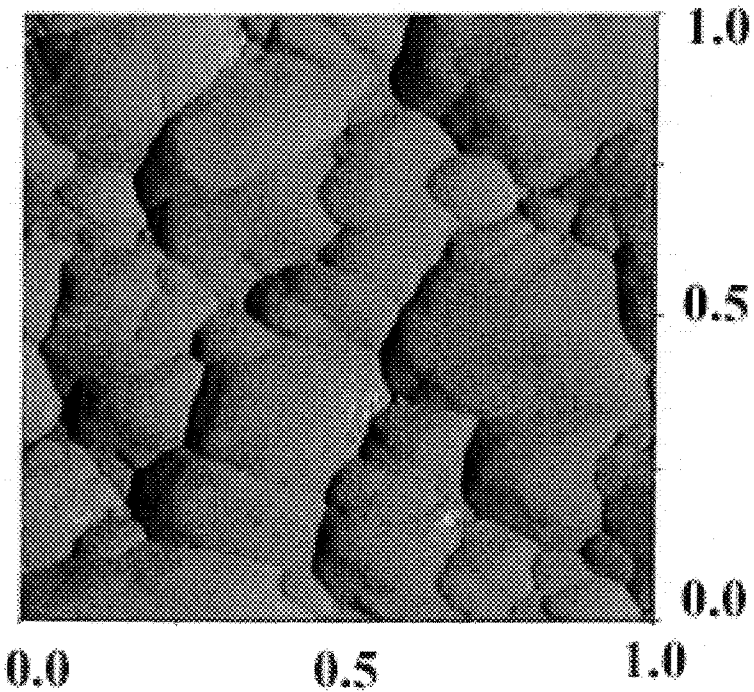
Lead Strontium Titanate ($Pb_xSr_{1-x}TiO_3$) Thin Films



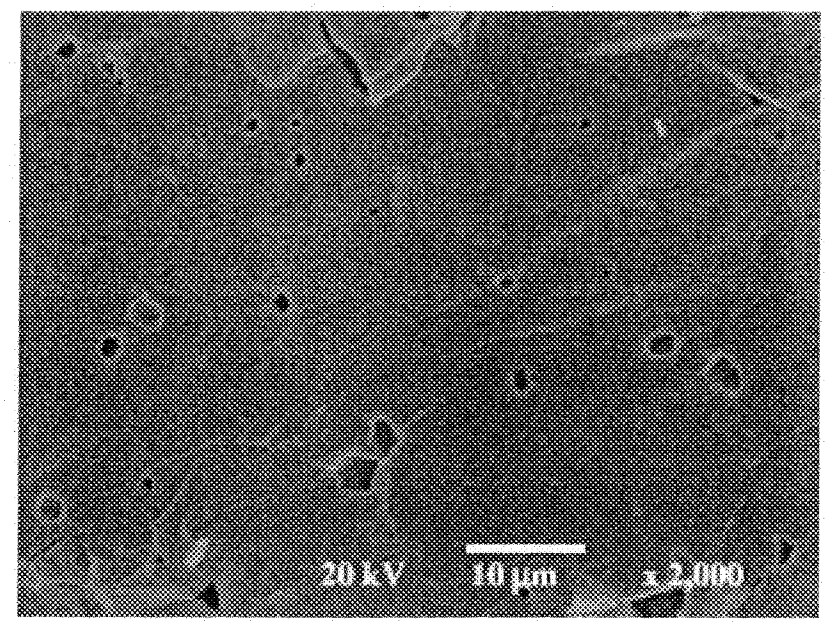
X-ray patterns of (a) PSTO Ceramic and (b) PSTO film

Ref: M. Jain, Y. Yuzyuk, R. Katiyar, Y. Somiya, A.S.Bhalla, F.A.Miranda, F.W.Van Keuls, Investigations of PbxSr1-xTiO3 Thin Films and Ceramics for Microelectronics Applications," 2004 Spring MRS Meeting, San Fracisco, CA.

Lead Strontium Titanate ($Pb_xSr_{1-x}TiO_3$) Thin Films



Surface morphology (1x1 μm) of PST30 film on LAO substrate



SEM image of the PST30 ceramic

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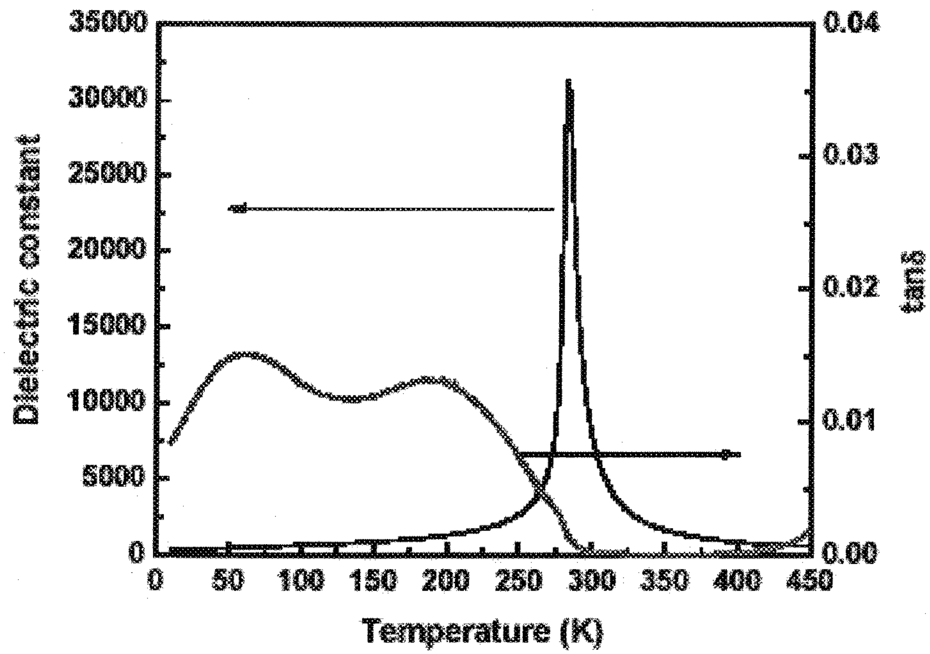
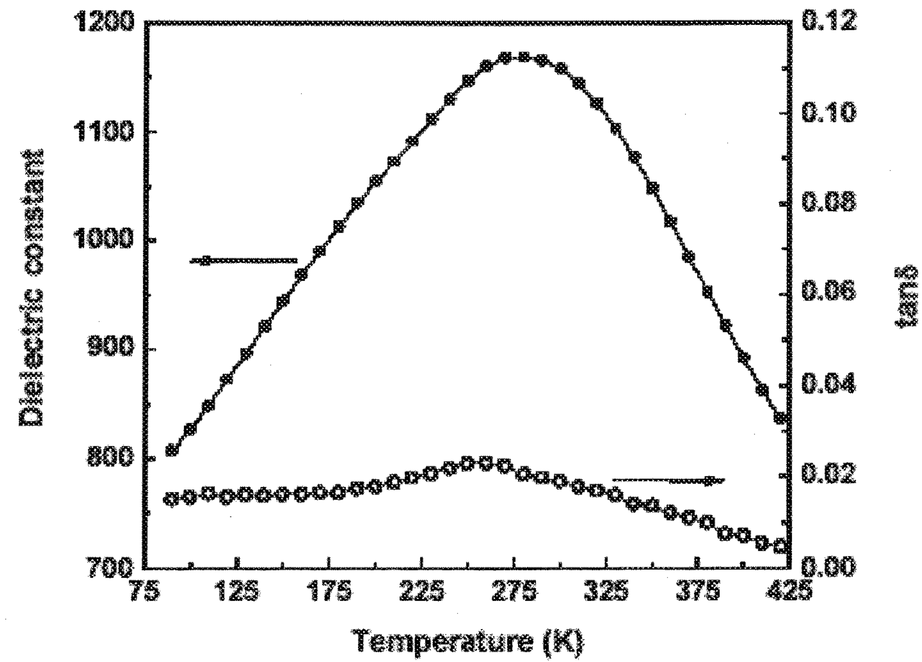
Lead Strontium Titanate ($Pb_xSr_{1-x}TiO_3$) Thin Films

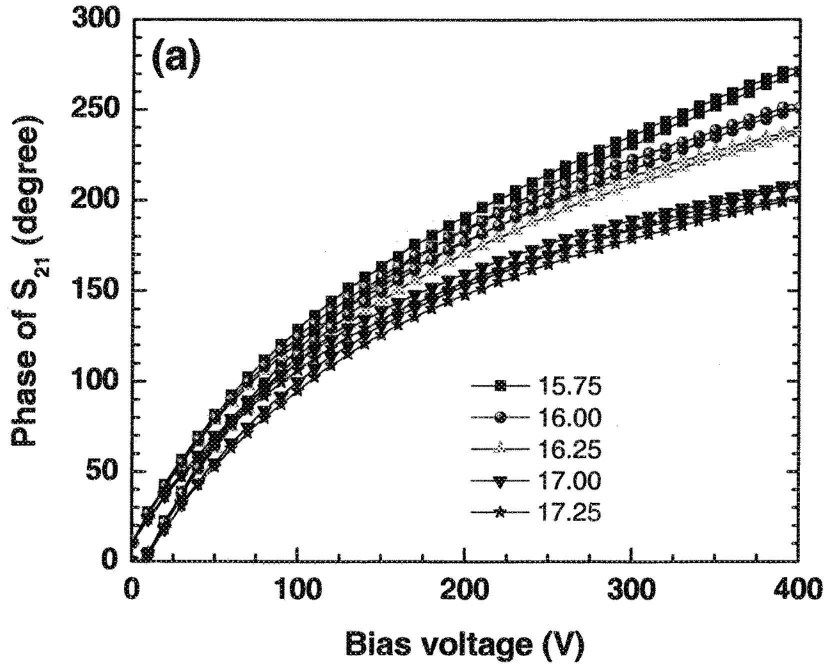


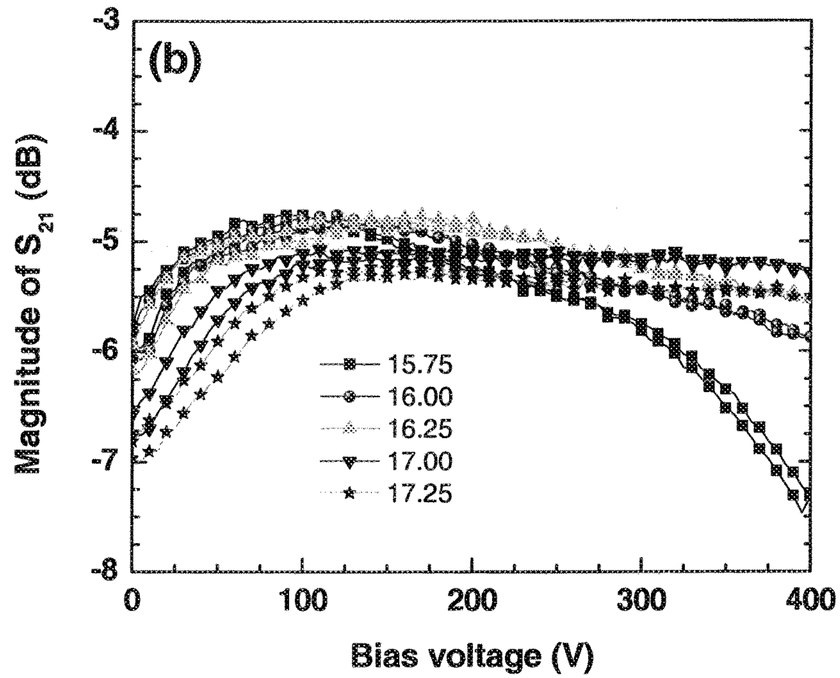
Temperature dependent dielectric constant and loss tangent for the PST30 Ceramic



Temperature dependent dielectric constant and loss tangent of the PST30 film on LAO

Lead Strontium Titanate (PbxSr1-xTiO3) Thin Films





Phase shifter characteristics of the PST30 film on LAO in terms of (a) Phase shift and (b) insertion losses at different frequencies.

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Lead Strontium Titanate (PbxSr1-xTiO3) Thin Films

High frequency characteristics of the eight element coupled phase shifter fabricated on PST30 film on LAO at maximum applied voltage (400V).

Frequency (GHz)	Maximum Phase shift, S_{21} (Deg)	Minimum Insertion loss (dB)	$K_{max.}$ (°/dB)
15.75	271	4.83	56.1
16.00	251	4.84	51.9
16.25	237	4.82	49.2
17.00	208	5.14	40.5
17.25	201	5.29	38.0

Conclusions

- Tunable ferroelectric devices have the potential to be highly applicable to emerging space-based communication network systems.

- Prototype resonators, filters, oscillators, and phase shifters have been fabricated and tested at K-band frequencies.

- Extensive materials analysis has been performed so as to optimize the tunability-to-loss figure of merit.

  - Precise lattice parameter, crystalline quality and thickness control
  - Ba/Sr ratio affects microwave performance.
  - Magnesium additions in BSTO and Pb additions in STO improve the microwave performance

- Statistical analysis of microstructural and microwave properties across 48 two-inch wafers indicates good reproducibility.

- Current efforts at GRC are centered on development of phased arrays where. beam steering is accomplished via ferroelectric thin film microstrip coupled line phase shifters.

Acknowledgements

- GRC's Space Communications and Data Systems (SCDS) Project
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