Thin Film $Ba_xSr_{1-x}TiO_3$ Coupled Microstrip Ku- and K-band Phase Shifters

F.W. Van Keuls, R.R. Romanofsky,
C.H. Mueller, J. W. Warner and F.A. Miranda

NASA Glenn Research Center
Cleveland, Ohio

Film Growers

J.S. Horwitz, W. Chang, and W.J. Kim

Naval Research Laboratory, Washington D.C.

C. L. Canedy, S. Aggarwal, T. Venkatesan, and R. Ramesh

University of Maryland, College Park, Maryland

J. W. Warner

NASA Glenn Research Center

TABLE OF CONTENTS

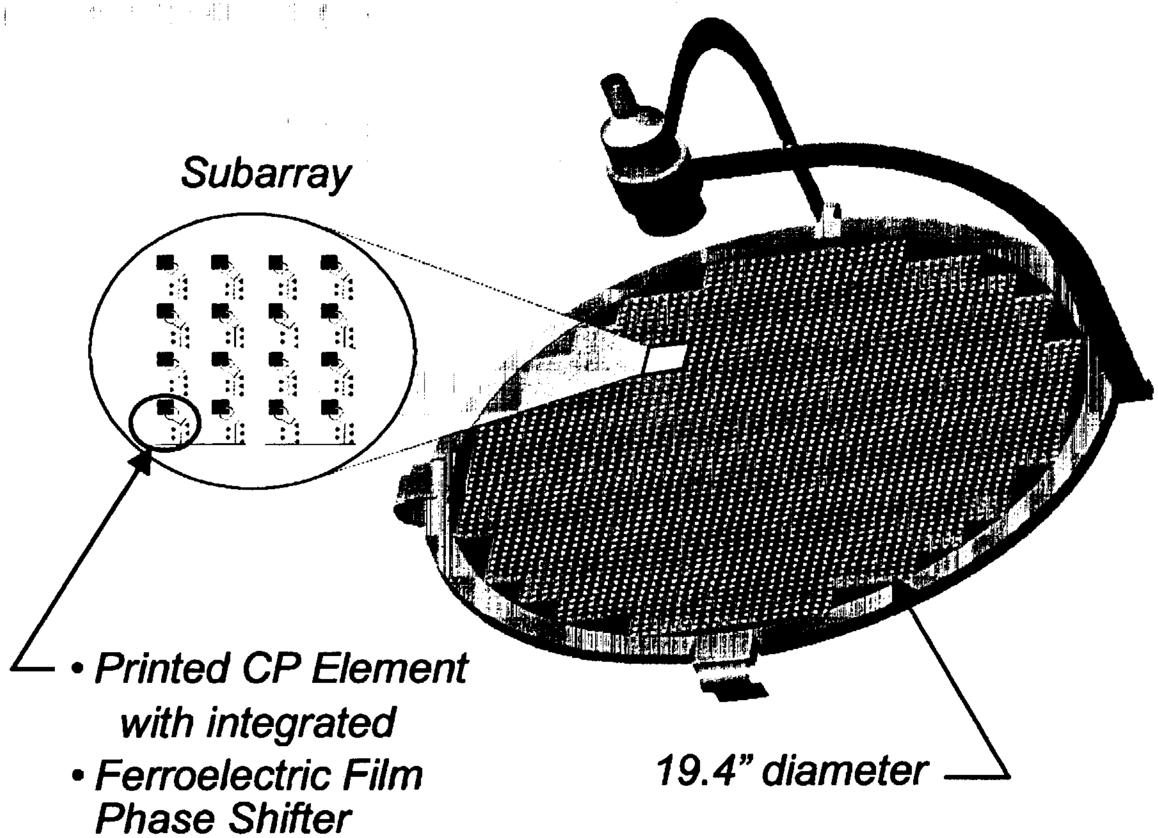
MOTIVATION

- Communications systems are steadily moving higher in frequency - beyond the useful range of tunable Si-based devices

- Our Objective: to use the dielectric nonlinearity of ferroelectric materials (in the paraelectric regime) to create smaller, lighter weight, planar (easy-to fabricate) cheaper tunable microwave components

- In particular, scanning phased array antennas are a critical technology future LEO satellites: both as vibrationless antennas on-board the satellites and as ground terminals in high data rate satellite constellations (e.g. Teledesic and Skybridge). Cheap, compact, low loss phase shifters will be an enabling technology for these applications.

Reflectarray Prototype



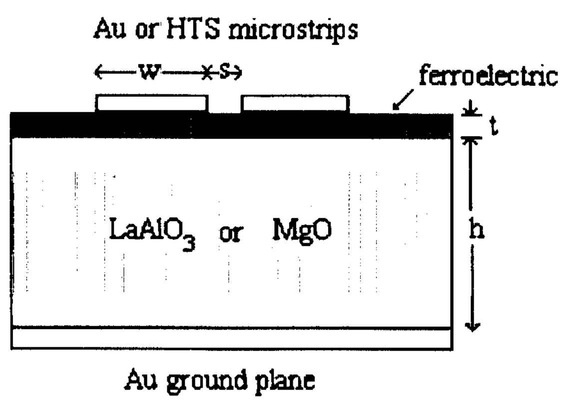
Characteristics

- 2832 elements - 176 16-element subarrays
- 3 dB insertion loss per phase shifter
- 39 dBi gain at 19 GHz

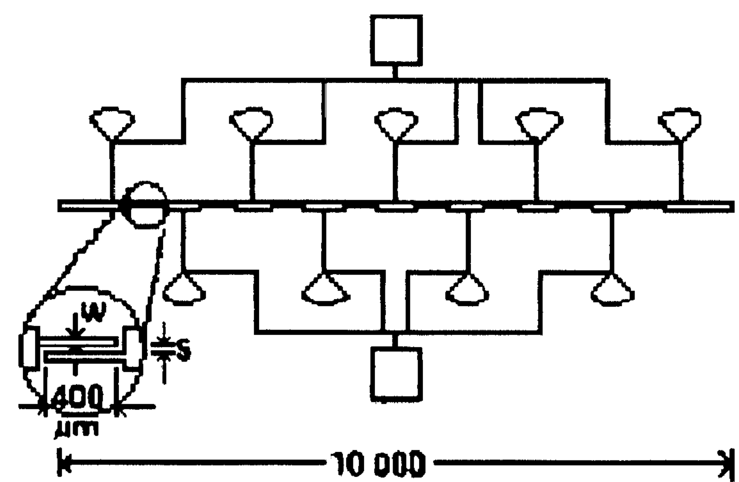
CETDP Product

Approach: Coupled Microstrip Phase Shifters (CMPS)

- Phase shifters consist of n-coupled microstrip sections
- Each section is a single pole broadband filter

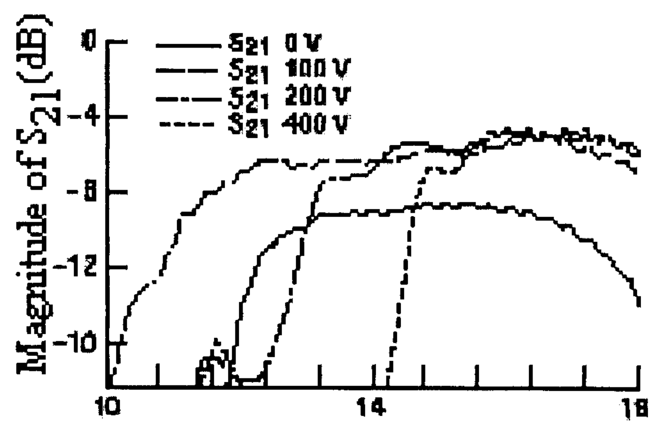


Cross-section of a CMPS section. For $LaAlO_3$ design w = 25 μm, s=7.5 μm, h =254 μm, t=1μm



Schematic of eight element CMPS on $LaAlO_3$. S = 7.5 μm and W = 25 μm.

- Passband shifts with $\varepsilon_r(V)$ as dc voltage is applied
- Phase Shift is proportional to n
- Resulting phase shifter is narrowband ~ 10% bandwidth
- Optimal frequency of operation depends on dc voltage, $\varepsilon_r(V)$ and film thickness



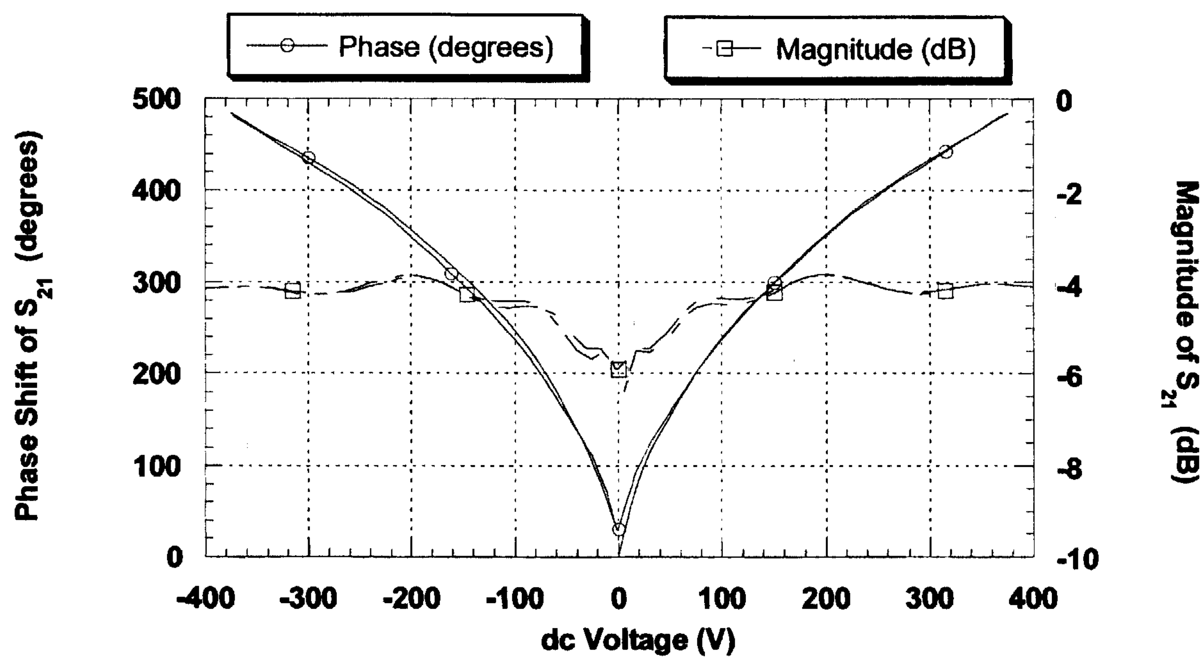
Frequency Dependence of $|S_{21}|$ for an eight-element LAO CMPS using YBCO/STO/LAO at 77 K

- BSTO films deposited by Pulsed Laser Deposition
  - at temperatures from 650 - 750 C
  - in a dynamic oxygen pressure of 100 mtorr
- Circuits fabricated on the films using chemical etching consist of
  - 15 nm Cr adhesion layer
  - 1.5 - 2.0 μm of Au
- Microwave circuits usually measured in vacuum but have also been measured in air after coating with bonding wax which has negligible effects on microwave measurement

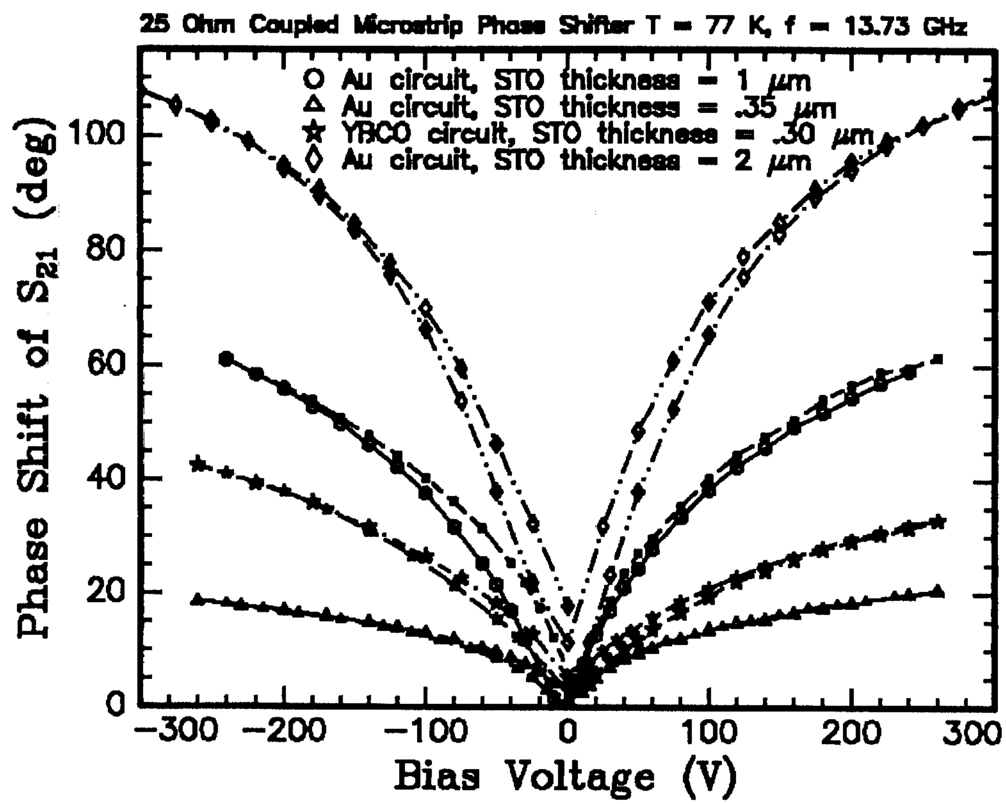
HTS/$SrTiO_3$/$LaAlO_3$ Cryogenic CMPS

- Phase shift per dB of loss, K = 80°/dB using 400 V dc

- Comparable in performance and size to solid state switched line phase shifters - better in continuous phase shift, cost and ease-of-fabrication



Phase shift and insertion loss of an eight element CMPS using YBCO (.35 μm) /$SrTiO_3$ (1.0 μm)/$LaAlO_3$ (254 μm). Data were taken at T = 40 K and 16 GHz.

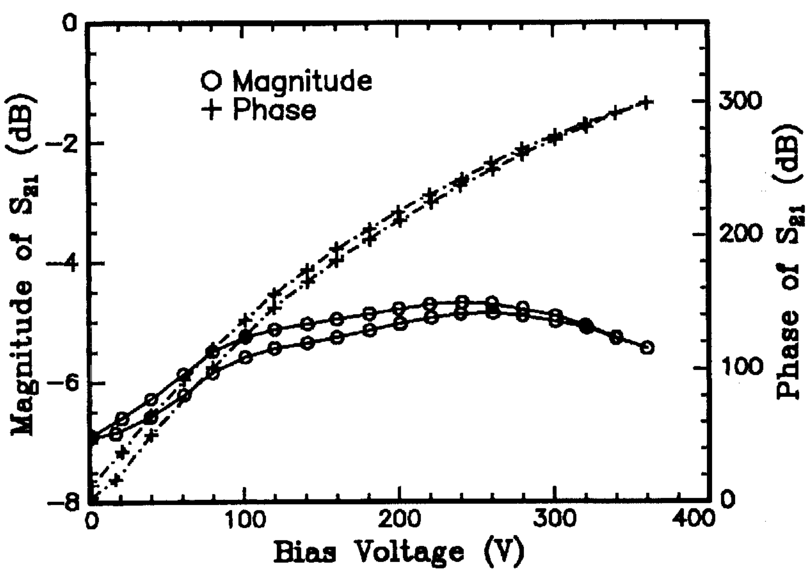


•Data from $SrTiO_3$ films showed that phase shift increased almost linearly with film thickness, actually closer to $\Delta\varphi \sim t^{0.67}$ in agreement with models

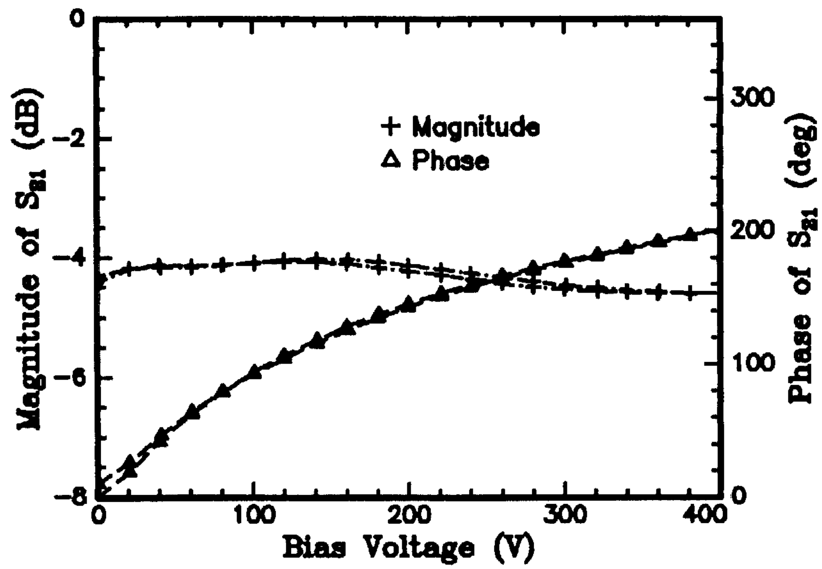
•If ferroelectric phase shift/loss is constant, then thicker films will yield better performance: lower overall loss since conductor loss is constant & more compact

Room Temperature $Ba_xSr_{1-x}TiO_3$ CMPS on $LaAlO_3$

- Using same CMPS design with Au/ $Ba_xSr_{1-x}TiO_3$/ LaAlO3 we have measured 299° and 43°/dB at 400 V dc bias



Room Temperature 8 element CMPS results using Au/BSTO/$LaAlO_3$ structure. Annealed 750 nm thick 40:60 BSTO film



Room Temperature 8 element CMPS results using Au/BSTO/$LaAlO_3$ structure. As-deposited 300 nm thick 50:50 BSTO film

- Best two phase shifters shown above showed 37.4° and 25°/ CM section

- Phase Shift and Insertion Loss Data for 9 Au/ $Ba_xSr_{1-x}TiO_3$/ $LaAlO_3$ CMPS

Tuning over 300 V dc range (except for Sample 2 where tuning decreased K)

Sample	Ba:Sr ratio	Thickness	Anneal at 1180 C for 7 hrs	f_{opt} (GHz)	Tuning at f_{opt} with 300 dc V	Max. Loss (dB) at f_{opt} over 300 V tuning range	Max K °/dB (w/ 300 V)
1	50:50	300 nm	none	14.3	168°	-4.5	37.3
2	50:50	300 nm	none	16	204°	-7.36	37.9 (<150 V)
3	50:50	300 nm	none	17	190°	-6.81	27.9
4	50:50	300 nm	none	17	167°	-6.35	26.3
5	60:40	650 nm	none	15	121°	-4.4	27.5
6	50:50	700 nm	none	15	206°	-6.43	32.0
7	60:40	1200 nm	none	15	74.8°	-3.17	23.6
8	50:50	1400 nm	none	13	180.5°	-6.86	26.3
9	40:60	750 nm	yes	14	274°	-7.01	39.1

- Film quality best compared at maximum phase shift/insertion loss, K (last column)

- Optimal frequency, f_{opt} depends on $\varepsilon_r(V)$ and film thickness
  i.e. larger $\varepsilon_r \Rightarrow$ lower f_{opt}, increased BSTO thickness $\Rightarrow$ lower f_{opt}

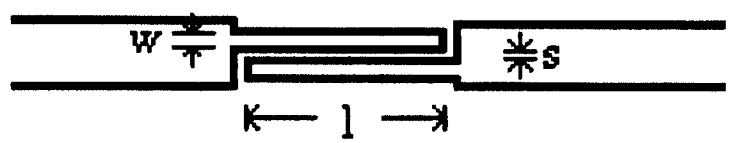
- Higher voltage usually leads to higher K, until the passband is shifted too high

- Highest K values seen for thinnest films or the one annealed film
- Thicker as-deposited $Ba_{0.5}Sr_{0.5}TiO_3$ films generally showed decreasing K with film thickness
- K values show correlation with film crystalline quality

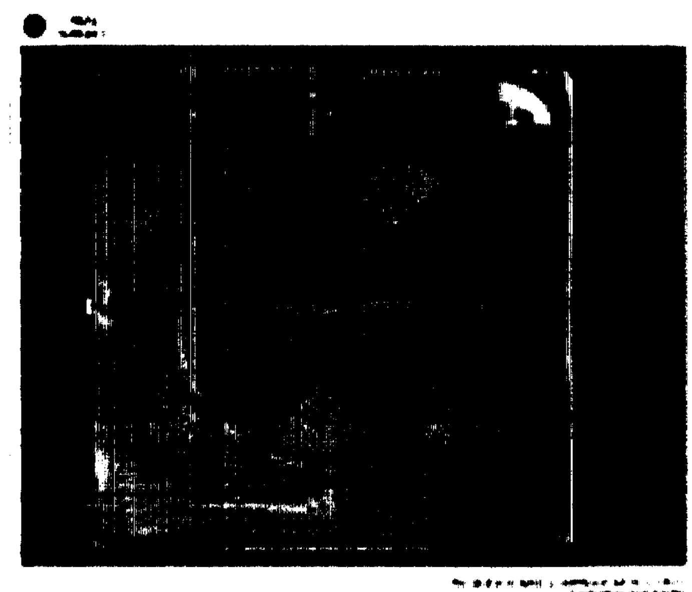
(to be discussed in Carl Mueller's talk)

$Ba_xSr_{1-x}TiO_3$ CMPS on MgO

- Different design for ε_r(MgO)=9.7 and 508 μm thick substrates
- Four element CMPS phase shifter: photo and dimensions below



Schematic of a single coupled microstrip section for this design on 508 μm thick MgO. s = 10 μm, l = 457 μm, and w= 56 μm.



Four element CMPS design on MgO which has achieved higher phase shift per loss at the cost of larger areas. The total length is 1 cm.

- MgO design has wider lines and less conductor loss but at the cost of larger dimensions

- Phase Shift and Insertion Loss Data for 5 Au/ $Ba_xSr_{1-x}TiO_3$/ MgO CMPS

Tuning over 400 V dc range

Sample	Ba:Sr ratio	doping	Anneal At 1100 C for 6 hrs.	Thickness (nm)	f_{opt} (GHz)	Tuning at f_{opt} with 400 dc V	Max. Loss (dB) at f_{opt} over 400 V tuning range	Max K °/dB (w/ 400
10	60:40	none	none	350	20	101.8°	-3.195	31.9
11	50:50	1% Mn	none	500	19.6	57°	-1.4	40.7
12	50:50	1% Mn	yes	500	16	75°	-1.95	38.5
13	60:40	1% Mn	none	500	15	114°	-2.1	54.3
14	60:40	1% Mn	yes	500	18	80°	-1.37	58.4

- Larger values of K, up to 58.4°/dB - but lower total phase shift: max 114°

- Phase shift per CM section similar to $LaAlO_3$: from 14.25° to 28.5°/ CM section

- Mn doped films showed a higher K value

In-depth look at the Four 1% Mn-doped 500 nm thick BSTO films on MgO substrates

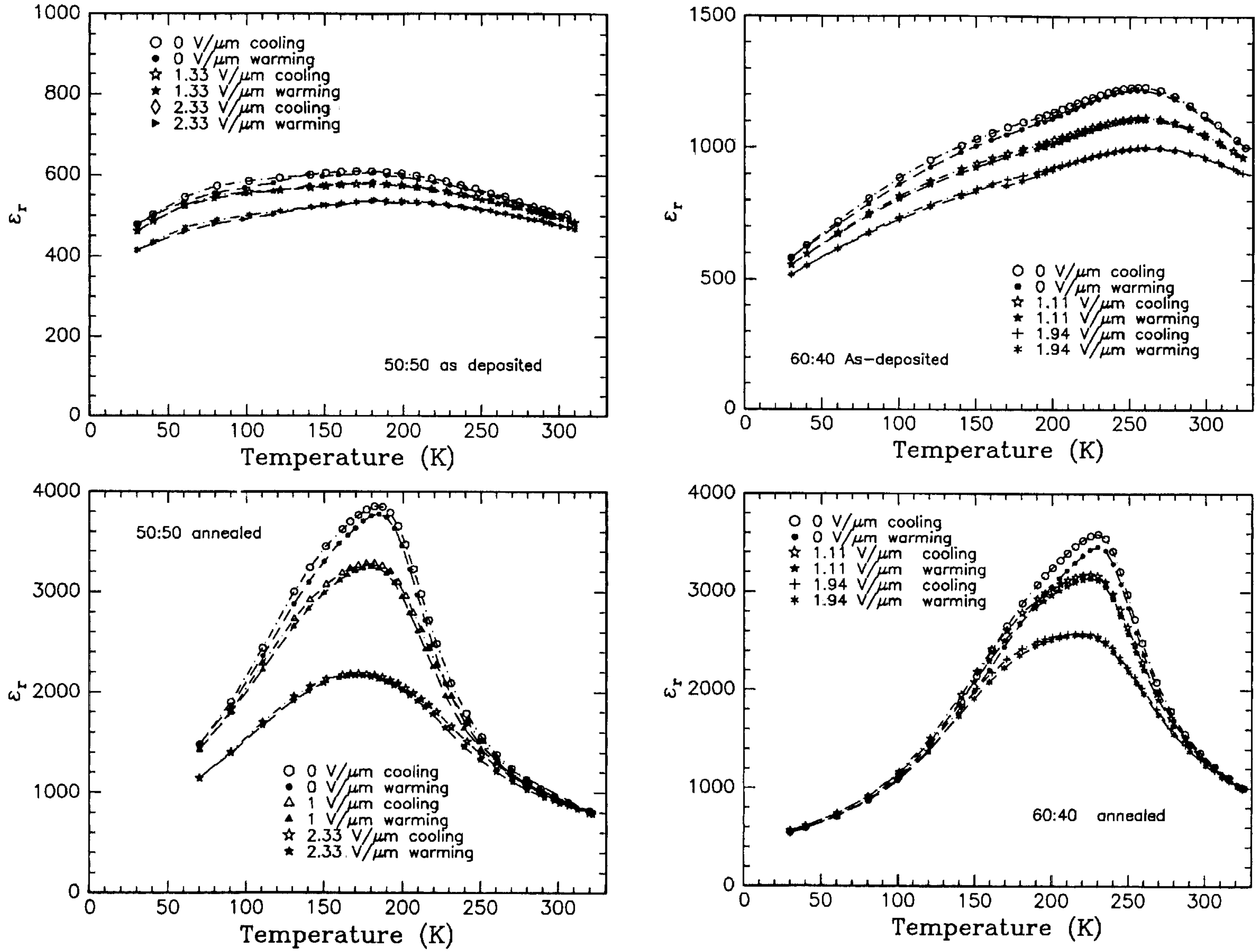
- Those films were first patterned with interdigital capacitors of dimensions: 100 fingers, finger width = 25 μm, gap = 15 μm, finger length = .691 cm

- Capacitance and tanδ measured at 1 MHz as a function of dc voltage and temperature

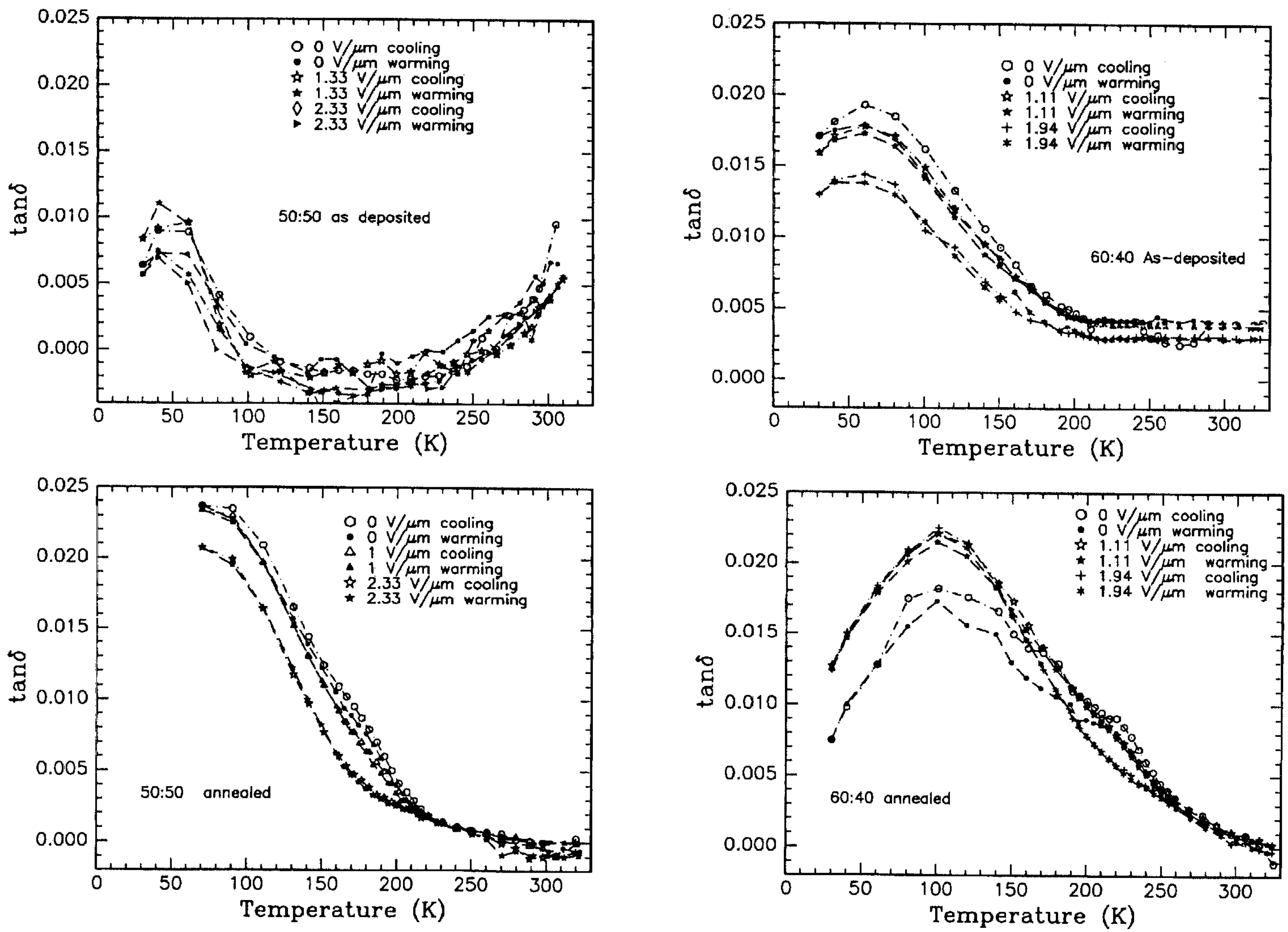
- ε_r derived using Gevorgian et al.'s[1] analysis which yields

$$C\ (pF) = 28.969 + 0.19780\varepsilon_r$$

[1] S. Gevorgian *et al.*, *IEE Proc.- Microw. Antennas Propag.*, **143**, 397 (1996).



The dielectric constant as a function of temperature for all four samples as derived from the capacitance of an interdigital electrode at 1 MHz.



The loss tangent as a function of temperature for all four samples, measured using an interdigital electrode at 1 MHz.

Observations about 1 MHz data:

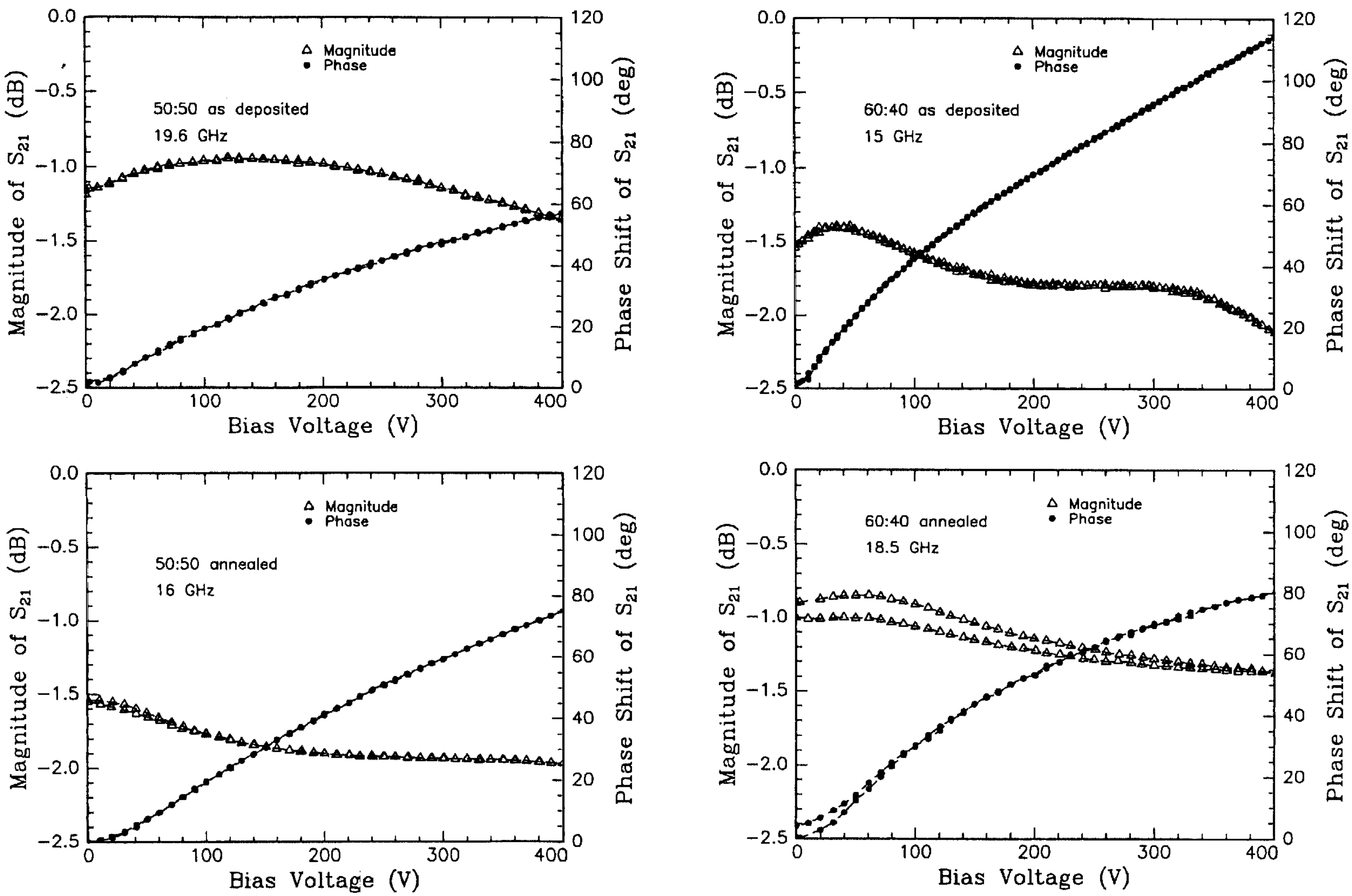
- Annealing increases ε_r by more than a factor of 2 near T_c
  $\tan\delta$ also increases, although only by 20% for the 60:40 films

- $\varepsilon_r(0)$ is quite high, maximum 3850 near T_c.
  Result echoes Wu and Barnes[2] finding that 1% Mn doping increased $\varepsilon_r(0)$

- Tc of annealed samples well below bulk values

50:50 film:	183 K	50:50 bulk:	230 K
60:40 film:	250 K	60:40 bulk:	284 K

[2] H.-D. Wu and F. Barnes, *Integrated Ferroelectrics*, **22**, 811 (1998).



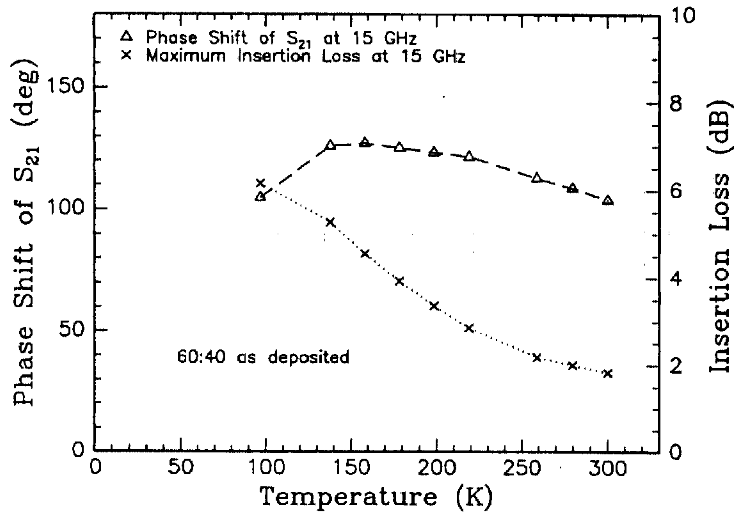
The phase shift and insertion loss through coupled microstrip phase shifters on each of the four samples at 298 K. Data is shown at f_{opt} for each sample.

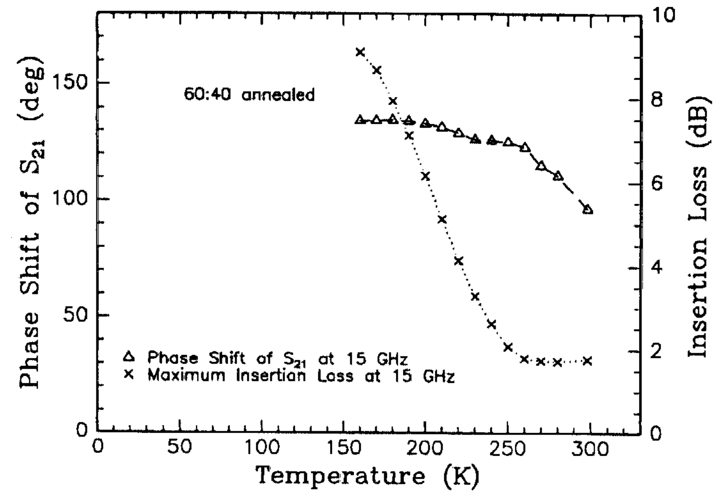
- Looking at $\varepsilon_r(V)$ and K, shows us that annealing doesn't have much effect at room temperature in these samples

- f_{opt} values agree with $\varepsilon_r(0)$ for samples 1-3: $\varepsilon_r(0) \Uparrow f_{opt} \Downarrow$

Ba:Sr ratio	Anneal at 1100 C for 6 hrs.	ε_r (0) at 1 MHz and 300 K	f_{opt} (GHz)	Tuning at f_{opt} w/ 400 V dc	Max. Loss (dB) at f_{opt} over 400 V range	Max K °/dB w/ 400 V dc
50:50	no	506	19.6	57°	-1.4	40.7
50:50	yes	946	16	75°	-1.95	38.5
60:40	no	1116	15	114°	-2.1	54.3
60:40	yes	1320	18	80°	-1.37	58.4

- Maximum phase shift (60:40 as-deposited) of 114° agrees with modeling where $\varepsilon_r(0) = 1000$ and $\varepsilon_r(E_{max}) = 300$





The phase shift of S_{21} (Δ) and maximum insertion loss (x) vs. temperature of the 60:40 samples. This data was taken at 15 GHz and using a 350 V dc bias.

- As-deposited sample shows 10% increase in phase shift with cooling similar to observed changes in $\varepsilon_r(0)$ at 1 MHz

- Annealed sample has 34% in phase shift from 300 to 220 K, compared to a 168% increase in $\varepsilon_r(0)$ at 1 MHz

- Conclude that either $\varepsilon_r(0)$ is much less at Ku-band than at 1 MHz

or

ε_r(40 V/μm) at Ku-band is much higher at 220 K than at 300 K

- 60:40 annealed phase shift is consistent with modeling where ε_r tunes from 1200 to 550 at 300 K, and from 3200 to 800 at 250 K

- Comparison between 1 MHz and 15-20 GHz data hampered by:

  1. Different E_{max} values: 2.3 V/μm at low-f
     40 V/μm at high-f

  2. Difficulty in modeling CMPS circuits and backing out $\varepsilon_r(V)$ and tanδ

  3. Nonlinearity in phase shift as a function of ε_r :
     CMPS phase shifter is more efficient at low ε_r than at high ε_r

Losses in $Ba_xSr_{1-x}TiO_3$ CMPS on MgO

- K parameter used in this talk is a measured device parameter

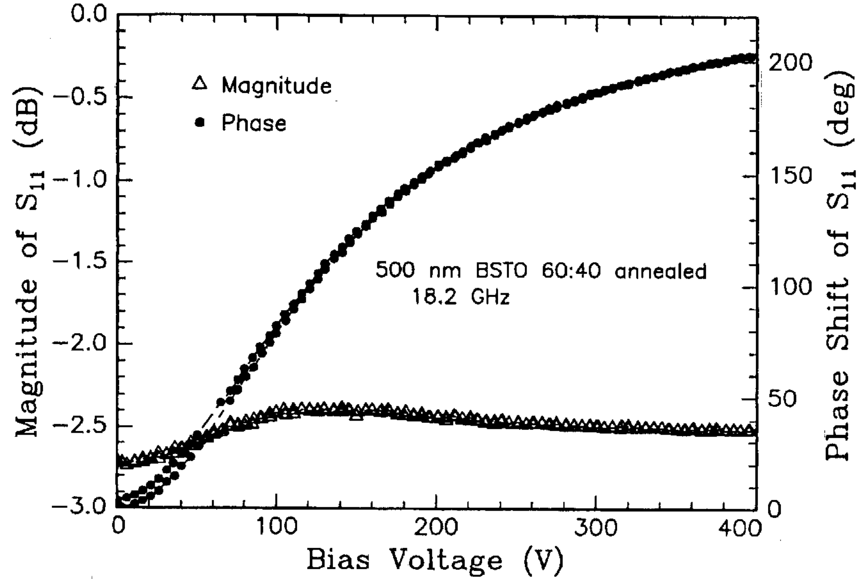
- losses included in K :

mismatch losses:	0.15 to 0.45 dB
substrate dielectric losses:	0.10 to 0.20 dB
conductor and radiation losses:	~ 0.5 dB

- remainder is ferroelectric loss:

60:40 annealed BSTO film:	0.62 dB or 45% of total loss
60:40 as-deposited film:	1.35 dB or 64% of total loss

Latest Improvements: new designs



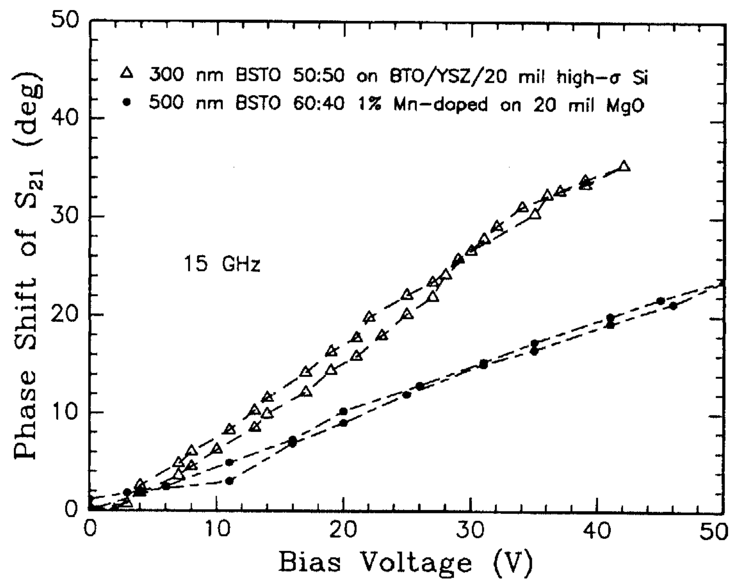
500 nm thick 50:50 BSTO 1% Mn-doped and annealed film on new 12 mil thick MgO design. Data taken in Reflection Mode. Largest room temperature K = 74.3°/dB

- Just starting selective etching of BSTO to remove tuning from the bias network

- radical new designs may find new ways of trading off bandwidth and voltage to improve performance

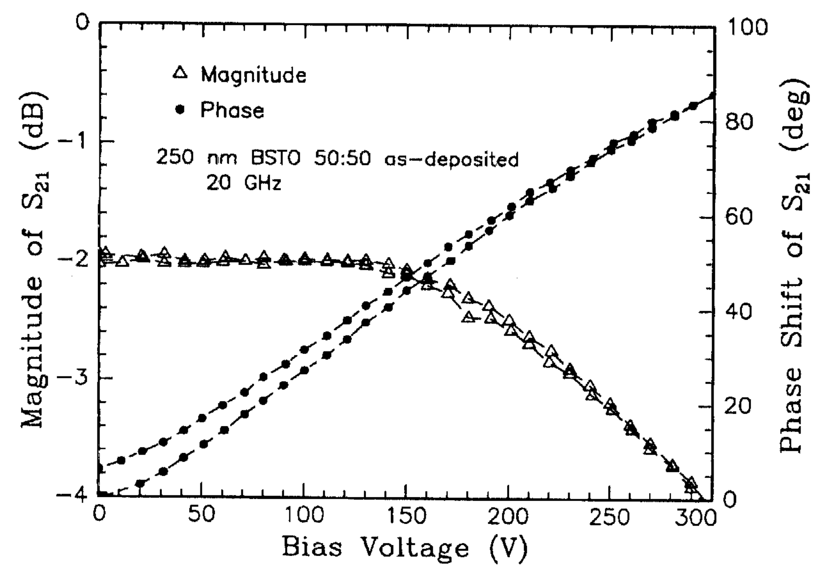
New cheaper substrates:

high-ρ Si

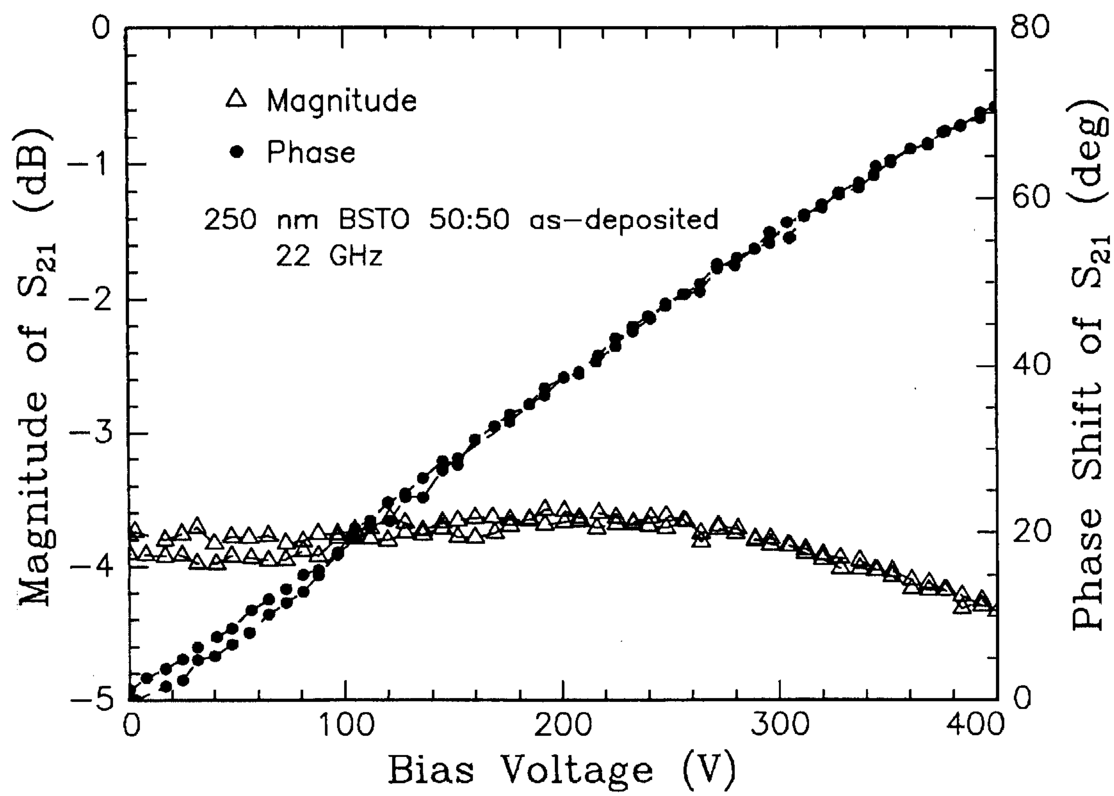


•Tunable BSTO grown on high -ρ Si with buffer layers. Problems with leakage through the Si - possibly due to contamination by Ag paint used to hold sample to heater

sapphire



•First try to grow BSTO on CeO_2 buffered (r-plane) sapphire yields reasonably tunable film with $K = 24°/dB$



- First try to grow BSTO on CeO_2 buffered alumina film with $K = 16°/dB$

SUMMARY

- Best room temperature CMPS performance seen on 1% Mn-doped $Ba_{0.6}Sr_{0.4}TiO_3$ annealed films on MgO:

  K = 74°/dB   Phase Shift/coupled length: 1427°/cm

- Attempt to improve phase shifters through thicker as-deposited films stymied by declining film quality with film thickness. Annealing may alleviate this problem

- CMPS phase shift at Ku-band didn't experience the great rise in tunability seen in 1 MHz $\varepsilon_r(0)$ data

- While CMPS circuits may be well suited for arrays, simpler circuits like CPW would be more useful for characterizing ε_r and $\tan\delta$ at Ku- and K-band

- New substrates and designs are being tested