Room Temperature Thin Film $Ba_xSr_{1-x}TiO_3$ Ku-Band Coupled MicrostripPhase Shifters: Effects of Film Thickness, Doping, Annealing and Substrate Choice

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Abstract: We report on measurements taken on over twenty Ku-band coupled microstrip phase shifters (CMPS) using thin ferroelectric films of $Ba_xSr_{1-x}TiO_3$. This CMPS design is a recent innovation designed to take advantage of the high tunability and tolerate the high dielectric constant of ferroelectric films at Ku- and K-band frequencies. These devices are envisioned as a component in low-cost steerable beam phased area antennas. Comparisons are made between devices with differing film thickness, annealed vs unannealed, Mn-doped vs. undoped, and also substrates of $LaAlO_3$ and MgO. A comparison between the CMPS structure and a CPW phase shifter was also made on the same ferroelectric film.

Introduction: Proposed low-earth orbiting satellite communication networks require low-cost steerable antennas to track the satellites. Thin film ferroelectric phase shifters incorporated into phased array antennas are one possible technology to fill this niche. They can provide compact voltage tunable low power devices. Much work has been done on the thin film ferroelectric $SrTiO_3$ which requires cryogenic operation. The most popular ferroelectric for room temperature operation is $Ba_xSr_{1-x}TiO_3$ (BSTO) where varying x can vary the maximum of the dielectric constant from 20 K to 395 K. BSTO films suffer from a high loss tangent which several groups are seeking to lower using dopants [1]. Another avenue for improving films consists of annealing to remove lattice imperfections and increase tunability [2]. The optimal film thickness is also a parameter of importance since device tunability increases with thickness but film quality generally decreases. This paper summarizes phase shifter results on about twenty different BSTO films.

Design: The phase shifter design consists of n-coupled microstrip sections in series. Each section functions as a single pole broadband filter whose passband shifts with dc bias applied to the ferroelectric. The phase shift is proportional to n. The resulting phase shifter is fairly narrowband, about 12% bandwidth, and the optimal frequency of operation, f_{opt}, depends upon the ε_r and thickness of the ferroelectric film. The device was first successfully demonstrated using $YBa_2Cu_3O_{7-\delta}$ atop a 1 μm $SrTiO_3$ ferroelectric film on a 254 μm thick $LaAlO_3$ substrate [3]. Those 1 cm long cryogenic devices demonstrated 484° of phase shift using 375 V dc bias with a figure of merit (K) of 80°/dB phase shift per maximum insertion loss. A photograph of a typical CMPS where n = 4 is shown in Figure 1.

Results: Transferring this exact design to a room temperature Au/0.3 μm BSTO/ $LaAlO_3$ structure[4] quickly achieved 200° phase shift and 43°/dB figure of merit (K) at 14 GHz and using 400 V dc bias [4]. Fig.2 illustrates the phase and magnitude of S_{21} through a biasing cycle of this device. Experience with $SrTiO_3$ devices indicated that the phase of S_{21} would increase almost linearly with film thickness while maintaining the same K. However, we found that simply increasing the $Ba_xSr_{1-x}TiO_3$ film thickness generally lead to minimal increases in phase shift and increased loss. Table 1 depicts this trend through the first seven listed devices that were deposited at the University of Maryland. Since the increasing ε_r and film thickness both lower the passband of the phase shifters, the different films are best compared through their K values at the point of optimal tuning given in the second to last column. The tuning and loss at 15 GHz are also given so that one may compare films at the same frequency. The values reported in the table are standardized to 300 V. Further tuning is possible, limited ultimately by device breakdown that occurs at field strengths in excess of 5×10^5 V/cm. The thicker BSTO films failed to maintain the larger K values of some 300 nm films. However, an annealed film from a different source of 0.75 μm thick film achieved 299° phase shift while maintaining 43°/dB at 14 GHz and 400 V dc bias. The larger K values and lower optimal operation frequencies which indicate higher ε_r were correlated with film crystalline quality and lattice parameter measurements taken from x-ray diffraction data.

A second set of four 0.5 μm BSTO films was grown at NRL on a 508 μm thick MgO substrate. These films are all doped with 1% Mn, two were annealed at 1100 C for 6 hours. A CMPS circuit with only 4 elements was patterned on these films. The smaller ε_r of MgO (9.8 instead of 25) and thicker substrate allowed wider lines and less conductor loss but at the cost of larger dimensions. The maximum K value of these films was 57 °/dB at 15 GHz but the maximum phase shift through the 1 cm devices was only 115 ° (using 400 V dc bias). A similar comparison of films shows that while annealing has a large effect at low temperatures near the Curie point (220 C) of these films, it does little at room temperature. An annealed BSTO compound with greater Ba concentration should show higher tunability at ambient temperature. Early results comparing Mn-doped and undoped films show that Mn-doping reduces the Curie temperature, but the impact of Mn doping on the K factor is small.

1. J. S. Horwitz, W. Chang, A.C. Carter, J.M. Pond, S.W. Kirchoefer, D.B. Chrisey, J. Levy, and C. Hubert, 'Structure/Property Relationships in Ferroelectric Thin films for Frequency Agile Microwave Electronics', Integrated Ferroelectrics, vol. 22, no. 1-4, pp. 799-809, 1998. H.-D. Wu and F. Barnes, 'Doped $Ba_xSr_{1-x}TiO_3$ Thin Films for Microwave Device Applications at Room Temperature', vol 22, no. 1-4, pp. 811-825, 1998.
2. L.A. Knauss, J.M. Pond, J.S. Horwitz, and D.B. Chrisey, C.H. Mueller and R. Treece, 'The effect of annealing on the structure and dielectric properties of $Ba_xSr_{1-x}TiO_3$ ferroelectric thin films,' *Appl. Phys. Lett.*, vol. **69**, no. 1, pp.25-27, 1996.
3. F.W. Van Keuls, R.R. Romanofsky, and F.A. Miranda, 'Several Microstrip-Based Conductor/Thin Film Ferroelectric Phase Designs Using ($YBa_2Cu_3O_{7-\delta}$, Au)/$SrTiO_3$/$LaAlO_3$ Structures', Integrated Ferroelectrics, vol 22, no. 1-4, pp. 893-901, 1998. F.W. Van Keuls, R.R. Romanofsky, D.Y. Bohman, M.D. Winters, F.A. Miranda, C.H. Mueller, R.E. Treece, T.V. Rivkin, and D. Galt, '($YBa_2Cu_3O_{7-\delta}$, Au)/$SrTiO_3$/$LaAlO_3$ thin film conductor/ferroelectric coupled microstripline phase shifters for phased array applications', *Appl. Phys. Lett.* Vol. **71**, no. 21, pp. 3075-3077, 1997.
4. F.W. Van Keuls, R.R. Romanofsky, N.D. Varaljay, F.A. Miranda, C.L. Canedy, S. Aggarwal, T. Venkatesan, and R. Ramesh, 'A Ku-Band Gold/ $Ba_xSr_{1-x}TiO_3$/LaAlO3 Conductor/Thin Film Ferroelectric Microstripline Phase Shifter for Room Temperature Communications Applications', *Microwave and Optical Technology Letters*, to be published January 1999.

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Fig. 1. A four element coupled microstrip phase shifter on a MgO substrate.

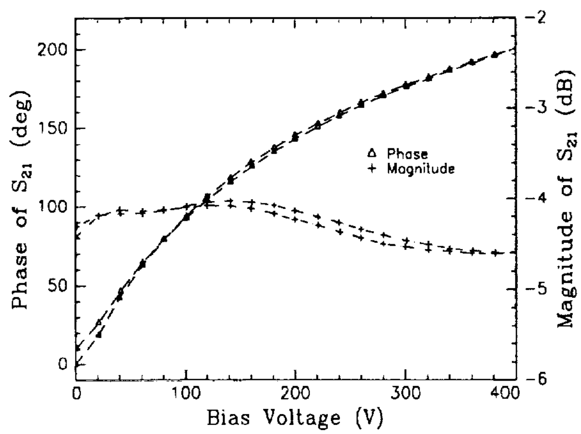

Fig.2. Data from eight element CMPS using a Au/0.3 μm BSTO/254 μm $LaAlO_3$ structure at room temperature.

Table 1. Eight element CMPS measurements on 10 mil $LaAlO_3$ substrates at room temperature. All values are given for tuning over a 300 V dc bias range.

Identity	Compo -sition	Thick -ness	f_{opt} (GHz)	Tuning at f_{opt} with 300 dc V	Max. Loss (dB) at fopt over 300 V tuning range	Tuning at 15 GHz with 300 dc V	Max. loss (dB) at 15 GHz	Max K °/dB (w/ 300 V)
NBST-001	50:50	300 nm	14.3	168°	-4.5	175°	-4.8	37.3
NBST-016	50:50	300 nm	17	190°	-6.81	240°	-12.4	27.9
NBST-015	50:50	300 nm	17	167°	-6.35	202°	-10.9	26.3
NBST-008	60:40	650 nm	15	121°	-4.4	121°	-4.4	27.5
NBST-017	50:50	700 nm	15	206°	-6.43	206°	-6.43	32.0
NBST-009	60:40	1200 nm	15	74.8°	-3.17	74.8°	-3.17	23.6
NBST-018	50:50	1400 nm	13	180.5°	-6.86	148°	-6.60	26.3
B111497B	60:40	750 nm	14	274°	-7.01	250°	-6.97	39.1