



# Life Cycle Testing of $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ Ferroelectric Thin Films in a Tunable Microwave Device

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## **LIFE CYCLE TESTING OF $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ FERROELECTRIC THIN FILMS IN A TUNABLE MICROWAVE DEVICE**

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Thin film ferroelectrics are being studied as candidates for novel tunable microwave components such as tunable filters, tunable oscillators, and phase shifters for applications in phased array antennas. Much work has been done optimizing the ferroelectric material and in producing proof-of-concepts of these components. However, little attention has been given to their reliability. In this study we present our results on the reliability of high quality K-band phase shifters made of  $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$  (BSTO) ferroelectric thin films (0.5-0.75  $\mu\text{m}$  thick) on MgO and LAO. The phase shift and insertion loss were measured at 300 K over  $10^4$  operation cycles within a 0-400 V dc bias range (0-40 V/ $\mu\text{m}$ ) at 15, 18, and 22 GHz. Results for these phase shifters indicate that in general there were no appreciable changes in phase shift after  $4 \times 10^4$  cycles, suggesting that these phase shifters are robust enough to sustain optimal performance under the operating mode typical of fast tracking phased arrays.

Keywords: Ferroelectric thin films;  $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ ; tunable microwave components; phase shifters; reliability; operating cycles; Ku- and K-band.

## I. INTRODUCTION

Ferroelectric thin films have received extensive attention lately because of their suitability for tunable microwave components. Promising results on the performance of ferroelectric thin film-based resonators, filters, oscillators, and phase shifters, have been steadily published during the past few years [1-4]. However, there still concern about the reliability of these components when subjected to working cycles involving fast switching between their “on” and “off” states (i.e., with and without an applied dc electric field). For example, a fast scanning phased array antenna used for tracking LEO satellites will required each phase shifting element in the array to undergo phase shift changes within seconds to satisfy the requirements of quick finding and tracking of each satellite in the LEO constellation. Furthermore, the mean time before failure (MTBF) of each of these phase shifters must be large enough to warrant their consideration for insertion into a satellite transceiver system (~5-7 years for LEO platforms) or ground tracking station at lower cost than current state-of-the-art (i.e., MMIC technology). In this paper, we have study the performance of several ferroelectric thin film-based phase shifters as a function of dc bias switching cycles in terms of their differential transmission and reflection phase shift and insertion loss.

## II. EXPERIMENTAL

In this study we have investigated K-band phase shifters made of  $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$  (BSTO) tunable ferroelectric thin films (0.5-0.75  $\mu\text{m}$  thick) on magnesium oxide (MgO) and lanthanum aluminate ( $\text{LaAlO}_3$ , heretofore LAO) dielectric substrates. The ferroelectric films consisted of laser ablated  $\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$ , 1% wt Mn doped, deposited on MgO (samples 1 and 2), and  $\text{Ba}_{0.50}\text{Sr}_{0.50}\text{TiO}_3$  on LAO (sample 3). For sample 1, the BSTO film is 750 nm thick and the MgO is 12 mil thick. For sample 2, the BSTO film is 500 nm thick and the MgO is 20 mil thick. Both samples were post-annealed at 1100 °C for 6 hr in an oxygen atmosphere after deposition. These samples were prepared by Dr. Horwitz’s group at the Naval Research Laboratory, Washington, D.C. [5]. For sample 3, the BSTO film is 400 nm thick and the LAO is 10 mil thick. This sample was prepared at NASA Glenn Research Center.

The phase shifter design consists of n-coupled microstrip sections in series. Each section represents a single-pole bandpass filter whose

passband shifts when a dc bias is applied to the ferroelectric. The total phase shift is proportional to  $n$ . In this particular case  $n = 4$  for samples 1 and 2, and  $n = 8$  for sample 3. The conducting layer of the coupled microstrip line phase shifters (CMPS) consisted of a 15 nm chromium adhesion layer, followed by 2  $\mu\text{m}$  gold layer sequentially deposited by electron beam evaporation. The patterning of the CMPS was performed using standard chemical etching techniques. Schematics for the cross-section of the generic multilayer configuration, the 8-element CMPS, and a picture of the actual four element CMPS circuit are shown in Fig. 1.

The dimensions of the CMPS are as follows: for sample 1, the coupling length between interdigitated fingers ( $\ell$ ) is 356  $\mu\text{m}$ , the

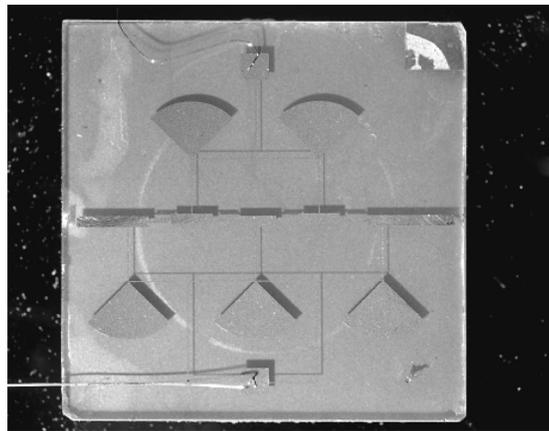
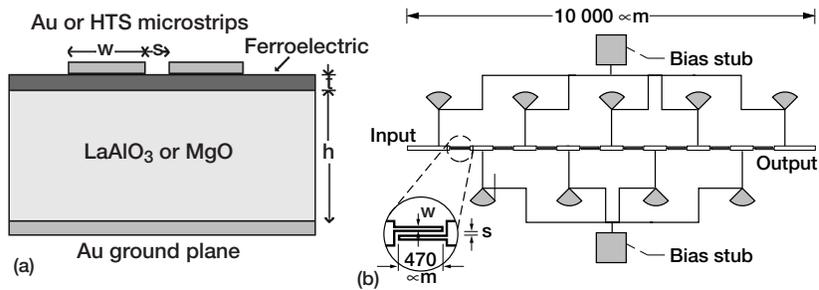


FIGURE 1. (a) Cross-section of a CMPS showing the separation distance between fingers ( $s$ ), the finger width ( $w$ ), the ferroelectric film thickness ( $t$ ) and the substrate thickness ( $h$ ). (b) Schematic of eight-element, CMPS.  $S = 7.5 \mu\text{m}$  and  $W = 25 \mu\text{m}$ . (c) A four-element Au/BSTO/MgO coupled microstrip phase shifter.

separation gap between fingers ( $s$ ) is  $10\ \mu\text{m}$ , and the finger width ( $w$ ) is  $30.5\ \mu\text{m}$ . For sample 2,  $\ell = 457\ \mu\text{m}$ ,  $s = 10\ \mu\text{m}$ , and  $w = 56\ \mu\text{m}$ . For sample 3,  $\ell = 470\ \mu\text{m}$ ,  $s = 7.5\ \mu\text{m}$ , and  $w = 25\ \mu\text{m}$ . The overall length of the phase shifters is 1 cm. These phase shifters are fairly narrowband ( $\sim 12\%$  bandwidth) and their optimal frequency of operation depends primarily upon the value of the ferroelectric dielectric constant ( $\epsilon_{\text{rBSTO}}$ ) and the thickness of the BSTO film.

To test the CMPS, these were placed inside a vacuum chamber under a vacuum of  $\sim 10$  mtorr. This was done to prevent arcing effects upon the application of the dc bias. During the measurements the sample was kept at  $300 \pm 0.1$  K using a temperature-controller. We decided to perform only room temperature measurements since this is the most likely temperature at which these devices will perform in actual communication systems. Data were taken by biasing the phase shifter from 0 to 400 V dc and back to 0 V. Each bias sweep lasted  $\sim 4$  sec, and phase shift and magnitude data were recorded every 50 cycles typically up to  $4 \times 10^4$  cycles, using a Labview-based fully automated measurement set-up. During the data recording cycle, the measurement of the data at each bias value took  $\sim 10$  sec. All the data shown in this paper correspond to measurements performed at 15, 18, and 22 GHz.

Measurements were also performed under standard temperature and pressure conditions (i.e., open air) to study the performance of the phase shifters under a real working environment. To accomplish this, the phase shifting elements were coated with  $\sim 2.0\ \mu\text{m}$  positive photoresist (AZ4210) ( $\epsilon_{\text{r}} \sim 3$ ) which protected the circuits from arcing effects.

### III. RESULTS

Figure 2 shows the magnitude and phase shift, respectively, for sample 1. Observe that for a given dc electric field value, both the magnitude and phase shift for this sample remained relatively the same up to  $4 \times 10^4$  voltage cycles. The data get slightly noisier at 0 V due to the intrinsic remnant electrical hysteresis associated with the ferroelectric film. However, note that at 300 V dc (or a field of  $30\text{V}/\mu\text{m}$ ) the values of the magnitude and phase data corresponding to each bias cycle are within  $\pm 0.015$  dB and  $\pm 1.5^\circ$ , respectively, from each other. This variation is inconsequential by comparison to customarily used phase shifter settings. That is, for a typical MMIC-based phase shifter, the insertion phase may vary by as much as 10 percent from the nominal setting [6].

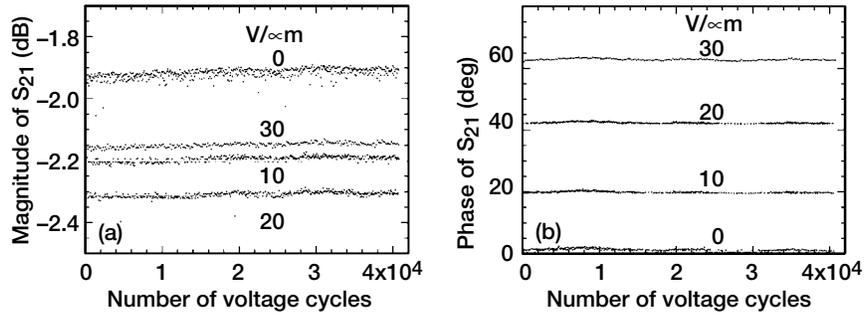


FIGURE 2. Transmission S-parameter ( $S_{21}$ ) insertion loss (a) and phase shift (b) versus voltage cycle for sample, 1 a Au ( $2.0 \mu\text{m}$ )/BSTO ( $0.75 \mu\text{m}$ )/MgO ( $305 \mu\text{m}$ ) four-element CMPS, at 18 GHz and 300 K. Ba:Sr ratio is 0.6:0.4.

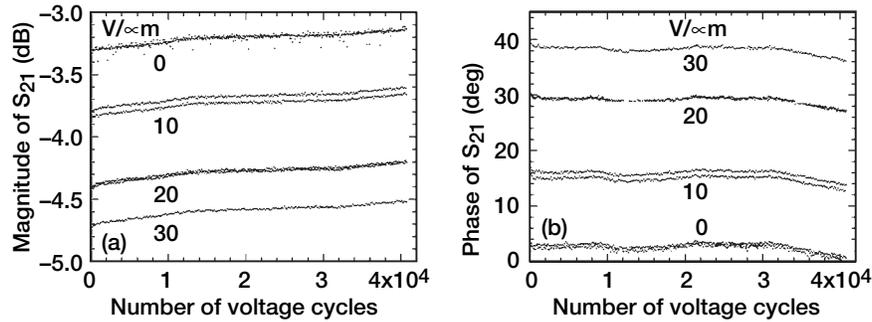


FIGURE 3. Transmission S-parameter ( $S_{21}$ ) insertion loss (a) and phase shift (b) versus voltage cycle for sample 2, a Au ( $2.0 \mu\text{m}$ )/BSTO ( $0.50 \mu\text{m}$ )/MgO ( $500 \mu\text{m}$ ) four-element CMPS, at 18 GHz and 300 K. Ba:Sr ratio is 0.5:0.5.

Figure 3 shows the magnitude and phase, respectively, for sample 2. Note that for all dc field values shown in these figures, sample 2 exhibits a variation of nearly 0.2 dB in insertion loss, and of nearly  $5^\circ$ , respectively, from its state at no cycling and its state at the end of  $4 \times 10^4$  cycle. Observe also that this sample exhibits higher insertion loss and lower phase shifts than sample 1 for the same bias values considered in this study. The higher losses exhibited by sample 2 are the result of 18 GHz being closer to the edge of its narrow passband than for the case of sample 1 in which the BSTO is  $250 \mu\text{m}$  thicker than the ferroelectric film in sample 1. Also, we have shown previously [2] that thicker the ferroelectric film the larger the phase shift obtained using the configuration under study, hence the smaller phase shift exhibited by sample 2 with respect to sample 1. The main point to emphasize here is

that both samples endured in a favorable way the rigors of the switching cycle to which they were subjected in this study.

Similar tests were done for sample 3. This sample differs from its counterparts on MgO in that this is an undoped sample. In the transmission mode this sample exhibits a discontinuity in the data after  $\sim 4,000$  cycles, after which there were no other observable discontinuities even up to  $7 \times 10^4$  cycles, as shown in Fig. 4. Data for this sample were also taken in the reflection mode ( $S_{11}$ ) reflection coefficient by terminating the phase shifter in an open, which is the configuration in which this phase shifters will be used in a electronically steerable reflectarray antenna [7]. Discontinuities can be observed in this mode also, as shown in Fig. 5. The primary source of these effects are still under investigation. Nevertheless, the large variations in  $S_{11}$  at zero bias for this sample may be alleviated by restricting the bias range to some non-zero voltage (e.g., 10 V).

Although the results presented above are encouraging, the real test, we were interested in developing an approach which allows for the operation of these phase shifters under ambient conditions (i.e., open air). To achieve this, we needed to prevent or diminish the probability of arcing when high bias were applied to the interdigital sections of the phase shifters. Therefore, we decided to coat these sections with low permittivity dielectrics such as teflon,  $\text{SiO}_2$ , and positive photoresist. The first two material did not work well, mainly because of uneven coating

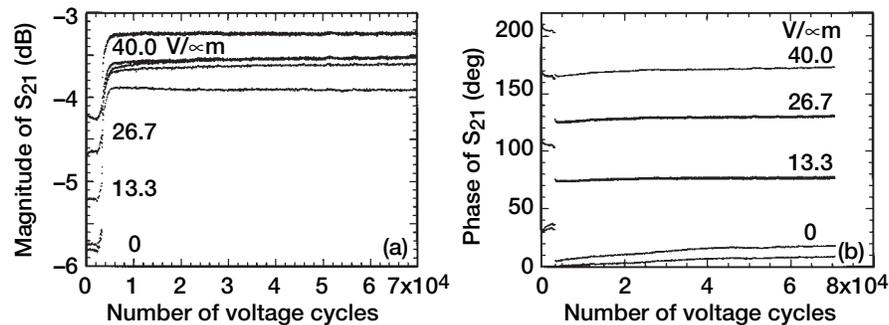


FIGURE 4. Transmission S-parameter ( $S_{21}$ ) insertion loss (a) and phase shift (b) versus voltage cycle for sample 3, a Au ( $2.0 \mu\text{m}$ )/ $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$  ( $0.50 \mu\text{m}$ )/LAO ( $254 \mu\text{m}$ ) eight-element CMPS, at 15 GHz and 300 K.

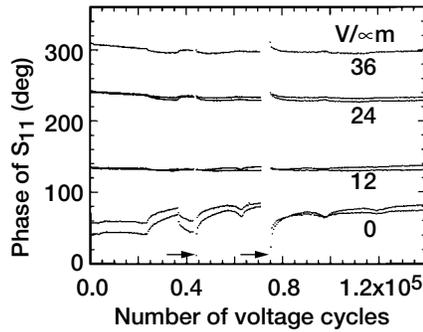


FIGURE 5. Relative phase shift of reflection S-parameter ( $S_{11}$ ) versus voltage cycle for sample 3, a Au ( $2.0 \mu\text{m}$ )/ $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$  ( $0.50 \mu\text{m}$ )/LAO ( $254 \mu\text{m}$ ) eight-element CMPS, at 15 GHz and 300 K. The arrows indicate re-starting of the measurement cycle.

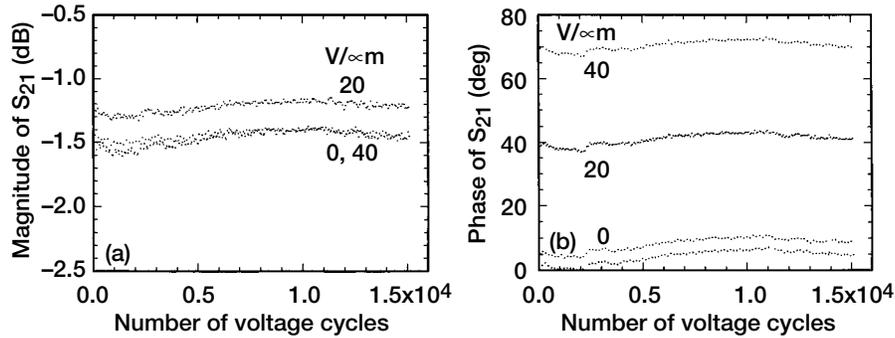


FIGURE 6. Transmission S-parameter ( $S_{21}$ ) insertion loss (a) and phase shift (b) versus voltage cycle for sample 1, a Au ( $2.0 \mu\text{m}$ )/ $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$  ( $0.75 \mu\text{m}$ )/MgO ( $305 \mu\text{m}$ ) four-element CMPS coated with photoresist and measured in air at 22 GHz and 300 K.

and flaking. However, we found that when using the photoresist, the phase shifters exhibited very good performance without any indication of degradation or discontinuities. Figure 6 shows the performance in open air of sample 1 after coating its interdigital sections with a layer ( $\sim 2 \mu\text{m}$  thick) of positive photoresist (AZ4210). Note that magnitude of the phase shift remained relatively the same as that shown in Fig. 1, while the insertion losses were reduced by nearly 1 dB for the applied fields considered in this effort. The reduction of the losses is due to

improved impedance matching while the remainder of the improvement could be due to the photoresist induced suppression of radiation losses via evanescent waves in the vicinity of the interdigital sections. More testing is still underway to strengthen the statistical meaning of these results. Nevertheless, the data presented so far show that ferroelectric-based phase shifters are suitable for insertion in fast scanning phased array antennas designed for room temperature operation at K-band frequencies and above.

#### IV. CONCLUSIONS

We have studied the performance of BSTO thin film ferroelectric-based phase shifters subjected to  $4 \times 10^4$  0-400 V dc bias switching impedance cycles (i.e., an electric field cycle of 0-40 V/ $\mu\text{m}$ ). No major changes in insertion loss or in relative phase shift were observed in any of the samples considered in this study after enduring the rigors of the aforementioned cycle. After coating the interdigital sections of the CMPS with photoresist, it was demonstrated that these phase shifters can perform flawlessly under open air conditions. These results suggest the feasibility of ferroelectric thin film-based technology to develop low cost and robust phase shifters for fast scanning phased array antennas designed for room temperature operation at K-band frequencies and above.

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