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Effect of Selectively Etched Ferroelectric Thin-film Layer on the Performance
of a Tunable Bandpass Filter

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ABSTRACT

The main purpose of this work is to study the effect of a selectively etched ferroelectric thin film layer on the performance of an electrically tunable filter. An X-band tunable filter was

designed, fabricated and tested on a selectively etched Barium Strontium Titanate (BSTO) ferroelectric thin film layer. Tunable filters with varying lengths of BSTO thin-film in the input and output coupling gaps were modeled, as well as experimentally tested. Experimental results showed that filters with coupling gaps partially filled with BSTO maintained frequency tunability and improved the insertion loss by ~2dB. To the best of our knowledge, these results represent the first experimental demonstration of the advantages of selective etching in the performance of thin film ferroelectric-based tunable microwave components.

I. INTRODUCTION

In the past few years, the use of high-permittivity ferroelectric materials in microwave devices has been widely investigated due to an increasing need for smaller size, lighter weight, higher power handling capability, and lower cost frequency and phase agile components. Examples of applications in the area of microwave engineering include field-dependent varactors, tunable resonators, filters, and phase shifters [1–5]. Ferroelectric thin films are suitable for frequency-agile microwave components due to the nonlinear dc electric field dependence of their relative dielectric constant. Strontium titanate (SrTiO_3 , henceforth STO) and Barium Strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$, henceforth BSTO) are the most popular ferroelectric thin films currently being studied for frequency agile components and circuits [1–5]. In recent years, proof-of-concept tunable components such as resonators, filters, couplers, diplexers, and phase shifters mainly for Ku-band (12 to 18 GHz) and K-band (18 to 26 GHz) frequencies have been demonstrated [4–6]. The majority of these components use coupled microstrip transmission line design, with a continuous layer of the ferroelectric thin-film between the transmission line and the substrate to provide frequency tunability. By applying a dc electric field between the coupled

microstrip lines, one can tune the relative dielectric constant of the ferroelectric thin-film, and thereby change the transmission characteristics. This effect results in frequency or phase agile components. The disadvantage is that ferroelectric materials introduce dielectric losses at microwave frequencies, which increase the device insertion losses. Furthermore, the dielectric losses of the ferroelectric are highest when the ferroelectric is unbiased. Since the tunability of the dielectric constant is obtained primarily by the electric field between the coupled lines, a continuous layer of ferroelectric thin-film provides the tunable film between the coupled lines necessary for tuning, but also results in regions where the ferroelectric layer is unbiased and contributes nothing to the overall tunability of the device. The untunable portions of the ferroelectric thus degrade the device performance by increasing insertion losses. It is the objective of this paper to find out the extent to which selective-etching approach can be used to reduce insertion losses without adversely affecting tunability. To the best of our knowledge this is the first such study on tunable filters on selectively etched BSTO.

II. DESIGN AND EXPERIMENTAL

The filter was designed for the center frequency of 7.4 GHz on 500- μm -thick lanthanum aluminate (LaAlO_3 , henceforth LAO) dielectric substrate with no ferroelectric thin-film layer present. The cross sectional view of the multilayered coupled microstrip line structure used in this tunable filter is shown in figure 1. The coupled microstrip line structure has a selectively etched ferroelectric thin-film layer (BSTO) of 0.3 μm on the LAO substrate, 2- μm -thick gold thin film for the microstrips, and 2- μm -thick gold ground plane deposited on the bottom side of the LAO substrate. Figure 2(a) shows the geometry of the tunable filter (top-view) with dimensions indicated. Figure 2(b) shows the top view of the etched pattern in the BSTO

ferroelectric thin-film layer. Note that the dimensions of the etched ferroelectric pattern are slightly larger for ease of alignment during the photolithographic process for the second step of conductor pattern definition. As shown in figure 2(b), the portion of the coupling gap filled with ferroelectric thin-film was varied from a length of 250 to 900 μm (entire coupled length). These filters were simulated using Sonnet em[®] electromagnetic simulation software.

The BSTO ferroelectric thin-films (Ba:Sr ratio of 60:40) used in this study were 300 nm thick, deposited on LAO substrates using a pulsed laser deposition (PLD) technique. Standard positive photolithography and wet chemical etching techniques were used for selectively etching BSTO thin-films. The BSTO was selectively etched in a 1:20 Hydrofluoric acid: DI H₂O solution. The etch rate for the BSTO thin-film was ~ 30 nm/min. A lift-off photolithography process was used for the fabrication of the gold-based filter circuit on the selectively etched BSTO. A gold layer of ~ 2 μm thickness was deposited for the ground-plane to complete the circuit fabrication. The filter circuits were packaged individually and tested inside a vacuum chamber to allow for high voltage biasing of the resonator, the input, and the output feed line sections. Voltages up to ± 500 V could be applied for testing the filters.

III. RESULTS AND DISCUSSIONS

The theoretical simulation results using Sonnet em[®] for the Au/BSTO/LAO multilayered microstrip bandpass filter are shown in figures 3 and 4, for the cases of varying lengths of the BSTO in the coupling gap region (900 and 250 μm). Figure 3 shows the simulated response for the filter with BSTO in the entire length of the coupling gap (i.e., $L_3 = 900$ μm), when the relative dielectric constant (ϵ_{rFE}) is assumed to be tunable from 3000 at zero bias to 300 at high

bias. The center frequency is tunable from 5.62 to 6.9 GHz, giving a frequency tunability of 1.28 GHz. For comparison, the center frequency of the same filter with no ferroelectric thin-film layer is 7.4 GHz and a bandwidth of 380 MHz. Figure 4 shows the simulated frequency response of S_{21} for a partial filling of BSTO in the coupling gap of only 250 μm . The center frequency shifts from 6.26 to 7.12 GHz when the ϵ_{rFE} changes from 3000 to 300, a frequency tunability of ~ 0.86 GHz.

The experimental results for the single pole filter were obtained by biasing the input, resonator, and the output sections, with alternative $\pm V$ bias, called the full bipolar bias [6]. That is, if the input and output sections were at a negative bias, then the resonator was positive or vice versa. Figure 5 shows the swept frequency response of S_{21} of a filter with BSTO in the entire length of the coupling gap (900 μm). The measurements were obtained for the applied dc bias from 0 to ± 400 V, at room temperature. The insertion loss for this filter at the center frequency of 7.7068 GHz was ~ 8.6784 dB at zero bias. The 3 dB bandwidth was ~ 350 MHz at zero bias. As the bias voltage is increased to ± 400 V, the center frequency of the filter was tunable by < 100 MHz. The change in insertion loss and the bandwidth were minimal in this sample. Figure 6 shows the swept frequency response of S_{21} for a filter with a partial filling of BSTO in the coupling gap of only 250 μm . The insertion loss for this filter was ~ 6.24 dB at zero bias, and improved to ~ 4.5 dB at ± 400 V, the lowest among the selectively etched BSTO based tunable filters studied. As shown in figure 6, the filter was tunable from ~ 7.596 GHz at zero bias to 7.746 MHz at ± 400 V, a frequency tunability of ~ 150 MHz. Another filter, with a partial filling of BSTO film in the coupling gap of 500 μm , exhibited the same amount of tunability (~ 150 MHz), with an insertion loss of 7.11 dB at zero bias, and no improvement in insertion loss with applied bias.

Comparisons between the simulated and experimental data uncovered the following information. First, for all of the gap lengths, the simulated results predict a much greater range of tuning (~8 times) than was observed experimentally. This is attributed to less dielectric tunability in the BSTO film, as compared to the large dielectric tunability assumed (ϵ_r tunable from 3000 at zero bias to 300 at high bias). Modeling the filters with ϵ_r tunable from 600 at zero bias, to 300 at high bias resulted in a frequency tunability comparable to the experimental results. Second, the simulated results indicate that reducing the length of the BSTO ferroelectric film in the coupling gap from 900 to 250 μm causes a decrease in frequency tunability. Preliminary experimental results indicate that the experimental tunabilities for the filters with partially filled BSTO in the coupling gaps of 500 and 250 μm , were virtually identical (~150 MHz), and comparable or higher than the frequency tunability for the filters with the entire coupled lengths filled by BSTO. Third, the high-field insertion loss for the filter with only 250 μm of BSTO in the coupling gaps was lower by >2 dB, compared to the filters with the lengths of BSTO in the coupling gaps of 500 and 900 μm . This result confirms the main advantage of selective etching, as one may be able to reduce the insertion loss of tunable filters without sacrificing frequency tunability. Nevertheless, more detailed work is underway with additional lengths of BSTO in the coupling gaps and with BSTO samples from different batches, to corroborate the aforementioned results.

IV. SUMMARY AND CONCLUSIONS

In summary, tunable bandpass filters were designed, fabricated and tested on selectively etched BSTO ferroelectric thin-films. Filters with varying lengths of BSTO in the coupling gaps

were studied for the first time. The frequency tunability of filters with partial filling of the BSTO in the coupling gaps of 500 and 250 μm were equal to or higher than that of filters with BSTO in the entire coupled lengths, while lowering the insertion loss by $\sim 2\text{dB}$. These results demonstrate the viability of this approach for reducing circuit insertion loss without adversely affecting tunability.

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FIGURE CAPTIONS

Figure 1.—Cross section of the two-layered coupled microstrip line structure used in this single pole filter. Width of the coupled lines $W = 165 \mu\text{m}$, and the spacing $S = 62.5 \mu\text{m}$.

Figure 2(a).—Schematic of a single pole tunable bandpass filter. Dimensions are: coupling gap $S_1 = 62.5 \mu\text{m}$, $L_1 = 1.15 \text{ mm}$, $L_2 = 0.9 \text{ mm}$. All microstrip lines are $165 \mu\text{m}$ wide.

Figure 2(b).—Top view of the patterned ferroelectric thin-film layer. Dimensions are: $S_1 = 62.5 \mu\text{m}$, $L_1 = 1.15 \text{ mm}$, $L_2 = 0.9 \text{ mm}$, and $L_3 = 0.25, 0.5, 0.9 \text{ mm}$. All lines are $190 \mu\text{m}$ wide.

Figure 3.—Simulated frequency response for the filter with the entire coupled length (0.9 mm) filled with BSTO.

Figure 4.—Simulated response for a filter with a partial filling of BSTO in the coupling gap of only 0.25 mm .

Figure 5.—Bias dependence of swept frequency response for a filter with the entire coupled length (0.9 mm) filled with BSTO, for $0, \pm 100, \pm 200, \pm 300$, and $\pm 400 \text{ V}$.

Figure 6.—Bias dependence of swept frequency response for a filter with a partial filling of BSTO in the coupling gap of 0.25 mm , for $0, \pm 100, \pm 200, \pm 300$, and $\pm 400 \text{ V}$.

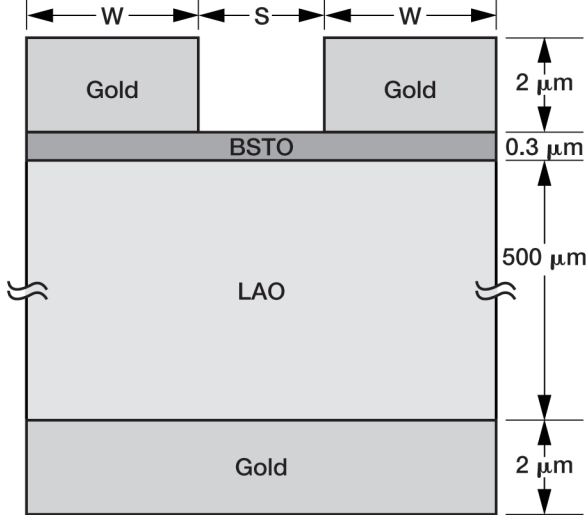


Figure 1.—Cross section of the two-layered coupled microstrip line structure used in this single pole filter. Width of the coupled lines $W = 165\ \mu\text{m}$, and the spacing $S = 62.5\ \mu\text{m}$.

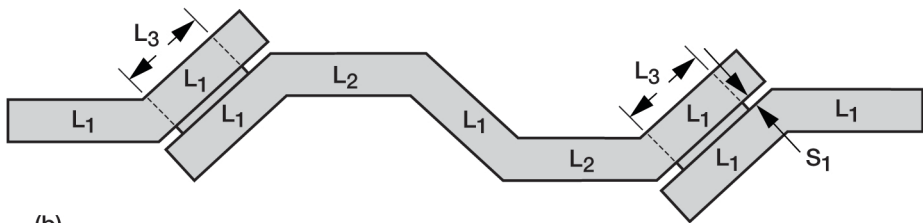
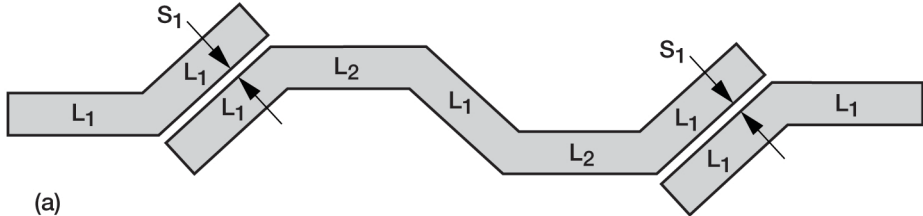


Figure 2a.—Schematic of a single pole tunable bandpass filter. Dimensions are: $S_1 = 62.5 \mu\text{m}$, $L_1 = 1.15 \text{ mm}$, $L_2 = 0.9 \text{ mm}$. All microstrip lines are $165 \mu\text{m}$ wide. (b) Top view of the patterned ferroelectric thin film layer. Dimensions are: $S_1 = 62.5 \mu\text{m}$, $L_1 = 1.15 \text{ mm}$, $L_2 = 0.9 \text{ mm}$ and $L_3 = 0.25, 0.5, 0.9 \text{ mm}$. All lines are $190 \mu\text{m}$ wide.

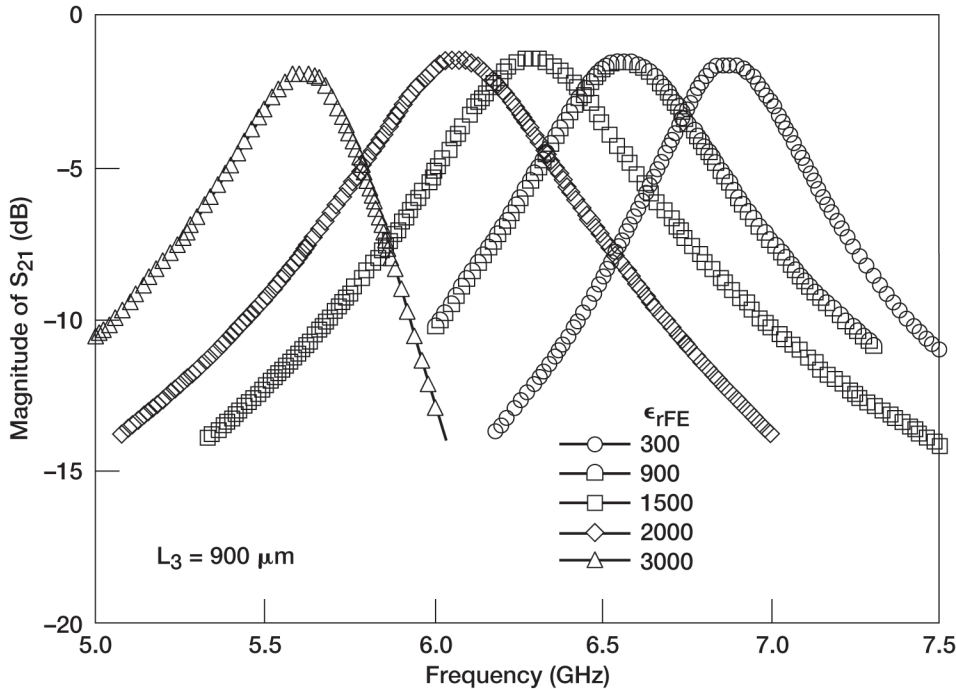


Figure 3.—Simulated frequency response for the filter with the entire coupled length (0.9 mm) filled with BSTO.

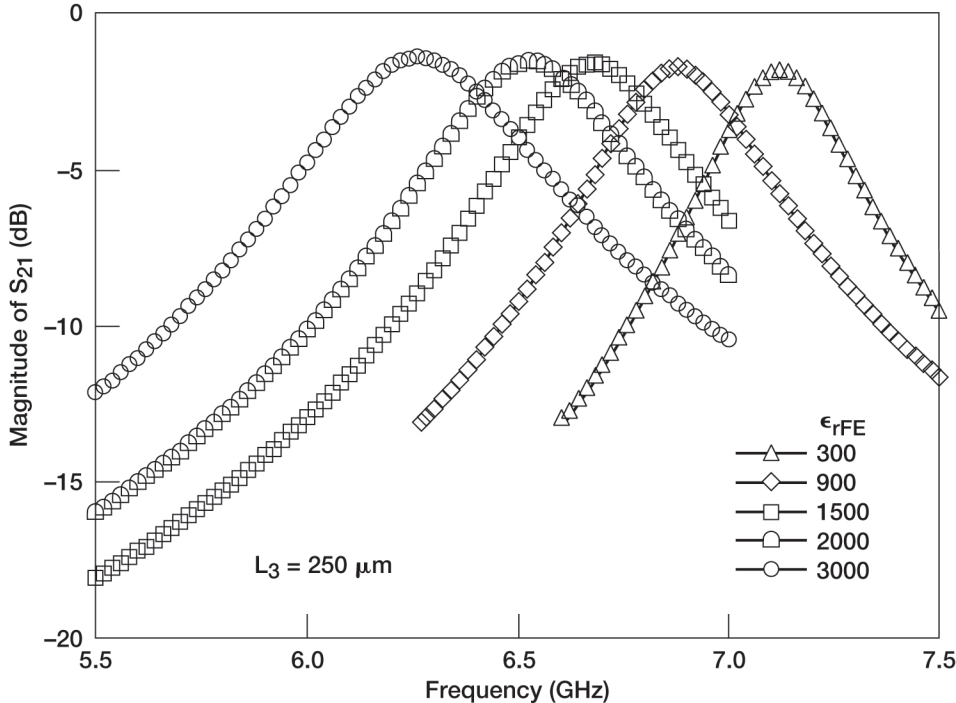


Figure 4.—Simulated response for a filter with a partial filling of BSTO in the coupling gap of only 0.25 mm.

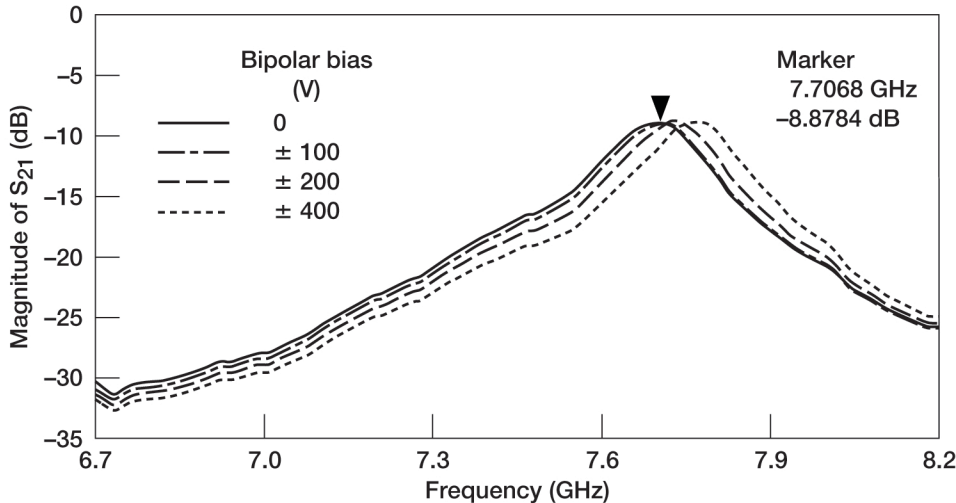


Figure 5.—Bias dependence of swept frequency response for a filter with the entire coupled length (0.9 mm) filled with BSTO, for 0, ± 100 V, ± 200 V, ± 300 V, and ± 400 V.

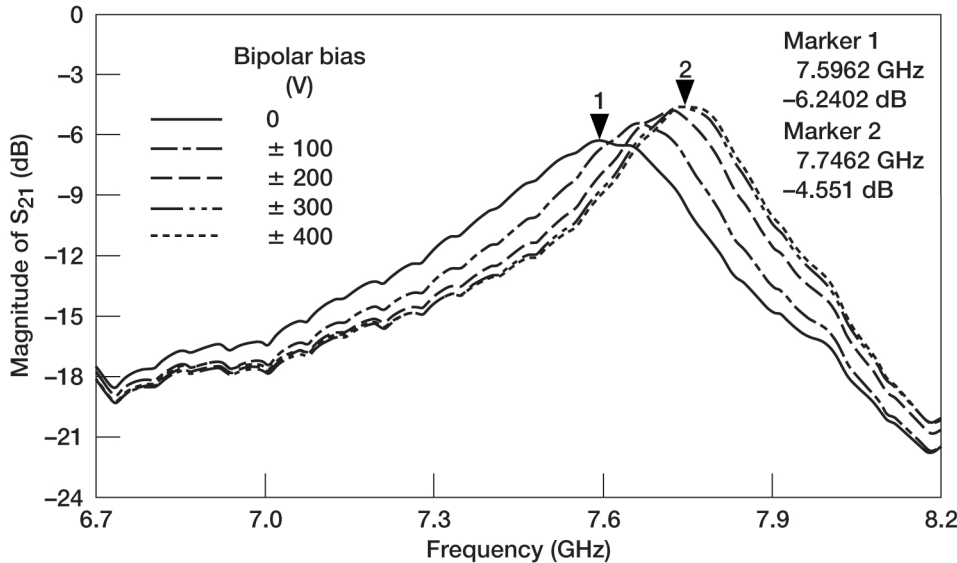


Figure 6.—Bias dependence of swept frequency response for a filter with a partial filling of BSTO in the coupling gap of 0.25 mm, for 0, ± 100 V, ± 200 V, ± 300 V, and ± 400 V.