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Performance Enhancement of Tunable Bandpass Filters Using Selective Etched Ferroelectric Thin Films

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ABSTRACT

The inclusion of voltage-tunable barium strontium titanate (BSTO) thin films into planar band pass filters offers tremendous potential to increase their versatility. The ability to tune the passband so as to correct for minor deviations in manufacturing tolerances, or to completely reconfigure the operating frequencies of a microwave communication system, are highly sought-after goals. However, use of ferroelectric films in these devices results in higher dielectric losses, which in turn increase the insertion loss and decrease the quality factors of the filters. This study explores the use of patterned ferroelectric layers to minimize dielectric losses without degrading tunability. Patterning the ferroelectric layers enables us to constrict the width of the ferroelectric layers between the coupled microstrip lines, and minimize losses due to ferroelectric layers. Coupled one-pole microstrip bandpass filters with fundamental resonances at ~7.2 GHz and well-defined harmonic resonances at ~14.4 and ~21.6 GHz, were designed, simulated and tested. For one of the filters, experimental results verified that its center frequency was tunable by 528 MHz at a center frequency of 21.957 GHz, with insertion losses varying from 4.3 to 2.5 dB, at 0 and 3.5 V/μm, respectively. These data demonstrate that the tuning-to-loss figure of merit of tunable microstrip filters can be greatly improved using patterned ferroelectric thin films as the tuning element, and tuning can be controlled by engineering the ferroelectric constriction in the coupled sections.

INTRODUCTION

Ferroelectric thin films have been investigated aggressively during the past decade in an attempt to create compact, electronically tunable microwave components for communication applications [1–4]. Interdigital capacitors using ferroelectric thin films have displayed tunabilities of up to 70% at 1 MHz [5,6] and proof-of-concept phase shifters have been demonstrated at frequencies up to 30 GHz [7–9]. We have learned many things from these efforts. For example, epitaxial films tend to exhibit the higher relative dielectric constants (ε_r) than polycrystalline films. We also have learned that film strain is detrimental to the tuning-to-loss figure of merit. Nevertheless, one aspect that is still challenging the imaginations of microwave engineers as well as material scientists alike is how to preserve the tunability of these films while minimizing RF losses. Although losses are still a major concern, it is evident that the attainment of the aforementioned goal is closely related to the particular circuit design under consideration.

Development of miniaturized, tunable narrowband ferroelectric bandpass filters for X-band (8 to 12 GHz) and higher frequency applications is appealing for several reasons. First, miniaturization of the filters is one of the key bottlenecks which delay advances in frequency-selective receiver functions [10]. Conventional passive distributed-element filters consume excessive space, whereas lumped-element filters introduce excessive transmission losses. Another problem which plagues miniaturized filter development is the difficulty of maintaining the production and accuracy standards necessary to develop filters. Microstrip coupled filters require dimensional standards that are difficult to meet in a production environment. The lack of a highly advanced means of introducing miniaturized, tunable filters into signal processing circuitry significantly hinders our ability to make use of available semiconductor materials.

Implementation of ferroelectric materials into narrowband filters has been difficult for several reasons. First, the losses in ferroelectric films used for microwave tuning applications are too high to be realistically considered in most filter applications. Narrowband filters create an especially difficult challenge for ferroelectric thin films, since coupled elements tend to be spaced far apart, thus creating a large ferroelectric area over which the signal must propagate as well as raising the voltage levels that must be applied in order to reach electric fields capable of tuning the ferroelectric.

In this paper, we describe a promising method of maintaining circuit tunability while reducing the losses. The basic premise of the work is that patterning highly constricted regions in the ferroelectric layer will reduce the displacement current between the coupled sections. Since the electric fields are concentrated in the constricted regions, this approach also enables non-uniform tuning (i.e., high tuning in the constricted region, low tuning away from it) of the ferroelectric layer. The circuit used to test our hypotheses is a one-pole bandpass filter. The results obtained so far will be discussed.

EXPERIMENTAL

The filters used in this study were designed for a center frequency of 7.4 GHz. Modeling of these filters was performed using Sonnet's em software. Note however, that currently available electromagnetic simulators have difficulty modeling the non-uniform field distributions induced by the presence of the ferroelectric in areas adjacent to the transmission lines. Thus, empirical demonstrations are required to determine the effectiveness of the approach considered in this paper as well as any other approach dealing with thin film ferroelectric based structures. Figure 1, shows a schematic of the filter structure used in the current study. Note that the ferroelectric film does not cover the entire area within the microstrips, as in typical microstrip design. Instead, its dimensions were varied (see Table I) so as to identify the parameters that most significantly impact on the overall filter performance. Note that the ferroelectric has a middle constriction that concentrates the electric field in the constricted area. Thus, the idea here is to determine if by following this approach we can preserve or enhance tunability and reduce losses.

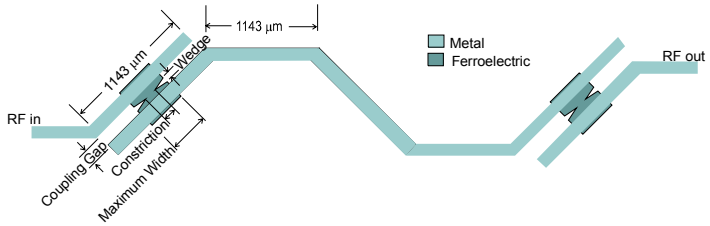


Figure 1: One-Pole Microstrip Filter with Etched Ferroelectric Layer

Table I: Variable Parameters for One-Pole Filter

Sample Number	Maximum Width (µm)	Constriction (µm)
A2	762	50.8
B2	508	50.8
C1	254	25.4
C2	254	50.8
C10	254	254

The filter used in this study was designed for a center frequency of 7.4 GHz (without ferroelectric) on a 254 μm thick lanthanum aluminate ($LaAlO_3$ henceforth LAO) substrate. In the ferroelectric version, the coupled microstrip line has a selectively etched $Ba_{0.50}Sr_{0.50}TiO_3$ (BSTO) ferroelectric thin film layer of 0.4 μm thickness grown on the LAO substrate by pulsed laser deposition. Standard positive photolithography and wet etching techniques were used to selectively etch the BSTO films. The BSTO was selectively etched in a 1:20 Hydrofluoric acid:DI H_2O solution, and the etch rate was approximately 30 nm/min. The etched ferroelectric layer is shown in figure 2. A lift-off photolithographic process was used for the fabrication of the gold filters. A gold layer ~2 μm was deposited for the ground plane to complete the circuit fabrication.

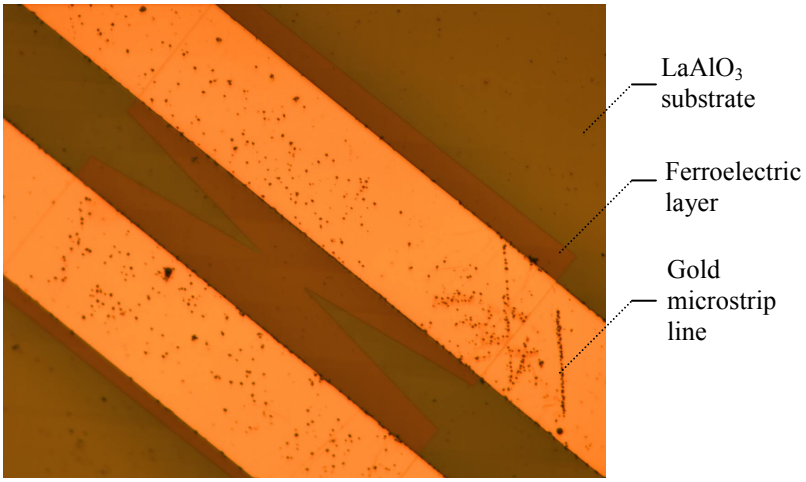


Figure 2. Coupled section of filter, showing etched ferroelectric layer.

For RF characterization the filters were tested inside a vacuum chamber to allow for high voltage biasing of the resonator. Voltages up to ± 400 volts dc could be applied for testing this filter. Since the width of the coupled gaps was 114 μm, the maximum electric field was 3.5 volts/μm. The transmission and reflection scattering parameters (S_{21} and S_{11}, respectively) were measured at room temperature using an HP 8510C network analyzer.

RESULTS

Figure 3.a shows S_{21} data for sample A2 (see Table I), over the frequency range 4 to 24 GHz. Note that the fundamental resonance of the filter at no bias is 7.27 GHz , but is lower than the design frequency due to the higher effective dielectric constant (ε_{eff}) resulting from the ferroelectric film. The first and second harmonics of the filter are clearly visible. Upon application of dc voltage (with the input and output microstrip lines kept at ground and the resonator positively biased), the filter exhibited a frequency tuning of 528 MHz at a center frequency of ~21 GHz. The insertion loss at zero bias field was 4.2 dB, and dropped to 2.8 dB when biased to 400 volts. Figure 3.b shows the S_{11} corresponding to the first harmonic of this filter. To isolate the mechanism(s) responsible for the loss and tuning characteristics, filters in which either a) the maximum width of the dielectric brick at the metal/dielectric interface; or b) the constriction of the ferroelectric block within the coupled section, were varied.

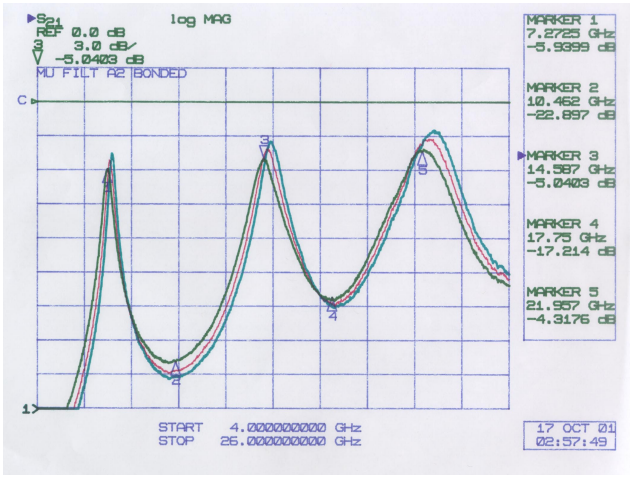


Figure 3.a. Transmission (S_{21}) versus frequency for filter A2, at bias levels of 0, 200, and 400 volts.

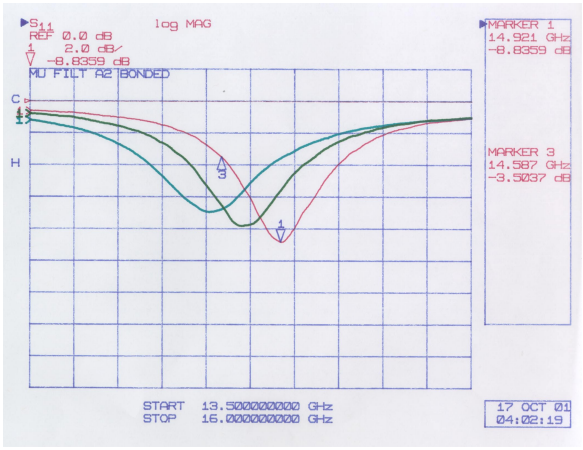


Figure 3.b. Reflection (S_{11}) versus frequency or filter A2, at bias levels of 0, 200, and 400 volts.

Figure 4 demonstrates the effect of reducing the maximum width of the ferroelectric (sample B2). Comparing A2 and B2, there was very little difference in microwave tuning or insertion loss for the fundamental resonance or first harmonic by reducing the width of the ferroelectric block from 762 to 508 μm, but maintaining the constriction at 51 μm. There is some degradation in the second harmonic, probably due to the diminished electromagnetic coupling at those frequencies. The effect of further decreasing the maximum width of the patterned brick to 254 μm, while maintaining the constriction at 51 μm, is demonstrated in figures 5.a and 5.b (sample C2). Once again, the frequency and tunability for the fundamental and first harmonic peaks are similar to those of the A2 and B2 filters. It appears that the maximum width of the patterned ferroelectric layer had little impact on the tunability and resonant frequency. At frequencies above the first harmonic, the shape of resonance was much better defined for the A2 sample than that of the B2 or C2 samples.

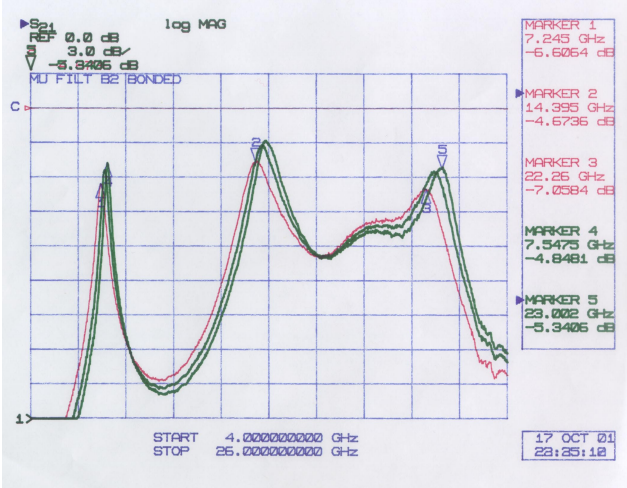


Figure 4. Transmission (S_{21}) versus frequency for filter B2, at bias levels of 0, 100, 200, 300 and 400 volts.

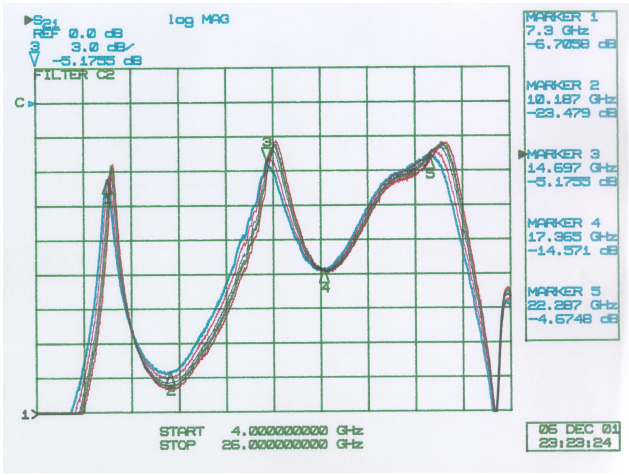


Figure 5.a. Transmission (S_{21}) versus frequency for filter C2, at bias levels of 0, 100, 200, 300 and 400 volts.

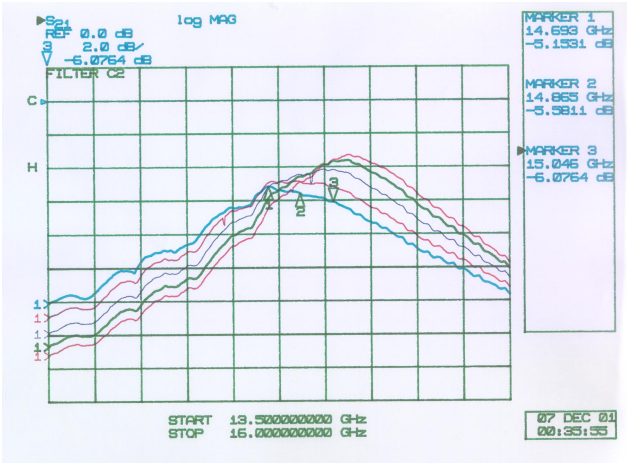


Figure 5.b. Transmission (S_{21}) versus frequency for filter C2, at bias levels of 0, 100, 200, 300 and 400 volts.

To investigate the manner in which the constriction affects filter performance, the maximum width of the patterned section (at the ferroelectric/microstrip interface) was held constant at 204 μm, and the constriction was either reduced to 25 μm (sample C1), or increased to 254 μm (C10). Since the maximum width and constriction of C1 and C10 were both 254 μm, there was no constriction in this sample. Although not shown in this paper, the microwave performance of C1 closely resembled that of C2, except the insertion losses were slightly higher. For example, the 0V insertion loss of the first harmonic peak (14.587 GHz) of C1 was 5.8 dB, and dropped to 4.2 dB with a 400 V bias. The resonant frequency was tunable by 320 MHz. By contrast, the 0V insertion loss of the first harmonic peak (14.697 GHz) of C2 was 5.1 dB, and dropped to 3.2 dB with a 400 volt bias. The resonant frequency was tunable by 457 MHz.

To further demonstrate the importance of the constriction, a filter with a 254 μm brick and no constriction (C10) was fabricated. The performance of this filter is displayed in figures 6.a and 6.b. This filter was markedly inferior to that of any of the filters with constricted ferroelectric layers. The insertion loss of the first harmonic peak (14.917 GHz) was 8.5 dB, and dropped to 6.5 dB with a 400 V bias. The resonant frequency was tunable by 180 MHz. The performance degradation was even more apparent in the fundamental resonance, where the 0V insertion loss was 15.56 dB. The 0V and 400 V insertion losses of the second harmonic were 6.8 and 5.3 dB, respectively.

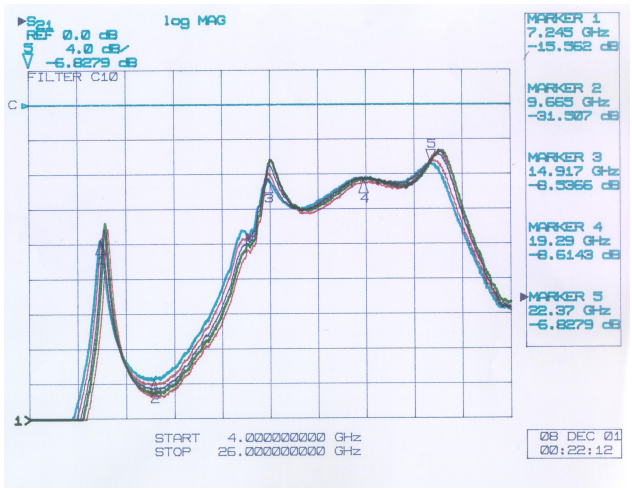


Figure 6.a. Transmission (S_{21}) versus frequency for filter C10, at bias levels of 0, 100, 200, 300 and 400 volts.

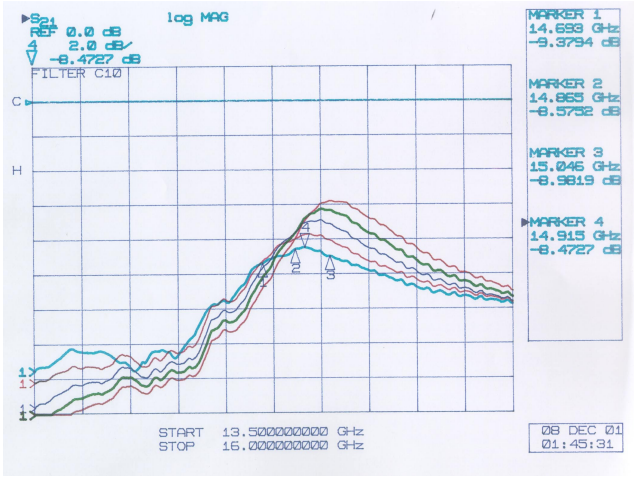


Figure 6.b. Transmission (S_{21}) versus frequency for filter C10, at bias levels of 0, 100, 200, 300 and 400 volts.

DISCUSSION

This study confirms that the most significant parameter affecting the tunability and loss of the filters is the constriction. The maximum width of the patterned ferroelectric had little impact on the resonant frequency of the fundamental or the first two overtones, or the tunability of each of these resonances. However, it appeared to have a substantial impact on the shape of the highest frequency (~21 GHz) resonance. The shape as well as the performance of the second harmonic of sample A2 was clearly superior to those with narrower widths at the electrode/ferroelectric junction, but identical constrictions (B2 and C2). Clearly, the constriction dramatically improved the microwave performance of the filter, and we believe the primary mechanism by which this performance enhancement is brought about is concentration of the electric field at the constricted region, thus creating a low ε_r region in the constricted region. Since this region is electrically connected in series with the surrounding high ε_r portion of the film (i.e. area outside of the constricted region), the effective dielectric constant and loss of the coupled region is substantially reduced.

Comparing samples C2 and C1, relatively minor changes were observed in tunability or insertion loss by decreasing the constriction from 51 to 25μm. It appears that for the filter design and ferroelectric patterning structure used in this set of experiments, the effect of the constriction on concentrating the electric fields and enhancing tunability is already maximized for the 51 μm constriction, and further reductions have a slightly deleterious effect.

Comparing samples C2 and C10 provides substantive evidence that the constriction was the key parameter that controlled tuning and insertion loss. Eliminating the constriction resulted in a very large drop in resonator performance for all three resonances, but the performance drop was particularly clear for the fundamental and first harmonic. The first harmonic insertion loss at 0V bias was over 2.5 dB worse than any of the filters that had a constricted ferroelectric layer. Furthermore, the tunability was less than 200 MHz. By contrast, the constricted filters displayed 320 (C1) and 457 (C2) MHz of tuning.

CONCLUSIONS

We have demonstrated that patterned ferroelectric filters have much better RF performance than unpatterned filters. The parameter responsible for the performance enhancement was the constriction, and we believe the constriction concentrates the electric fields in a narrow region within the coupled section.

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13. ABSTRACT ***(Maximum 200 words)***

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