



Correlation of Electric Field and Critical Design Parameters for Ferroelectric Tunable Microwave Filters

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**CORRELATION OF ELECTRIC FIELD AND CRITICAL
DESIGN PARAMETERS FOR FERROELECTRIC
TUNABLE MICROWAVE FILTERS**

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The correlation of electric field and critical design parameters such as the insertion loss, frequency tunability, return loss, and bandwidth of conductor/ferroelectric/dielectric microstrip tunable K-band microwave filters is discussed in this work. This work is based primarily on barium strontium titanate (BSTO) ferroelectric thin film based tunable microstrip filters for room temperature applications. Two new parameters which we believe will simplify the evaluation of ferroelectric thin films for tunable microwave filters, are defined. The first of these, called the sensitivity parameter, is defined as the incremental change in center frequency with incremental change in maximum applied electric field (E_{PEAK}) in the filter. The other, the loss parameter, is defined as the incremental or decremental change in insertion loss of the filter with incremental change in maximum applied electric field. At room temperature, the Au/BSTO/LAO microstrip filters exhibited a sensitivity parameter value between 15 and 5 MHz/cm/kV. The loss parameter varied for different bias configurations used for electrically tuning the filter. The loss parameter varied from 0.05 to 0.01 dB/cm/kV at room temperature.

I. INTRODUCTION

Tunable microwave components based on the nonlinear electric field dependence of ferroelectric thin films such as strontium titanate (SrTiO_3) and barium strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$) are attracting attention in the microwave research community.^[1-5] SrTiO_3 , also referred to as STO, is suitable for low temperature applications below 77K, as one can reduce its relative dielectric constant by more than a factor of 5 by applying a dc electric field.^[4] $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$, also referred to as BSTO, on the other hand, can be tailored to be a room temperature tunable ferroelectric, as one could reduce its relative dielectric constant by more than a factor of 5 at or near room temperature.^[5] Tunable resonators, bandpass filters, and phase shifters have been successfully demonstrated using thin films of these two materials in the past few years.^[1-6] Large tunability higher than 15% have been reported in tunable filters, and resonators based on the ferroelectric thin films.^[3] In addition, we have recently reported on K-band tunable bandpass filters using conductor/ferroelectric/dielectric substrate multilayered microstrip configuration.^[6-7] However, a detailed work on the effect of electric field on the important circuit parameters in ferroelectric tunable microstrip filters is still necessary. In this work, we have thoroughly analyzed the effect of the applied electric field (primarily responsible for tunability in these planar filters) on the parameters such as the insertion loss, center frequency, the return loss, and the bandwidth of the microstrip bandpass filters based on the conductor/ferroelectric/dielectric substrate multilayered microstrip configuration. The largest applied electric field is an important parameter in microstrip filters, since circuit geometries could result in unequal electric fields in different portions of the circuit. The smallest gap will have the largest electric field for a given bias, and for the purpose of this paper it is defined as the peak electric field (E_{peak}). Also, E_{peak} allows for better comparison between filters with different geometries. Based on the analysis, we propose two new performance evaluation parameters which we believe will be of importance for microwave applications of the ferroelectric tunable components. The first is called the sensitivity parameter, defined as the slope of the center frequency versus the E_{peak} curve. The second parameter, called the loss parameter, is defined as the slope of the insertion loss versus the E_{peak} curve. The sensitivity parameter is important for fine tuning the filter for the required center frequency with as minimal an applied electric field/bias as possible. Since the ferroelectrics are nonlinear dielectric materials, the sensitivity factor will also be

varying in a nonlinear fashion. Knowing the center frequency or frequency shift versus the maximum applied electric field or the maximum and minimum sensitivity factors in the operating range of the electric field would help in fine tuning the filter's operation. The loss parameter on the other hand gives the insertion loss variability with electric field. Ideally, one would like to operate in a region where the variability of insertion loss with electric field is minimal. One may be able to reduce the insertion loss by choosing the right bias configuration, as will be demonstrated in this work.

II. DESIGN

The filters were designed with edge coupled half wavelength resonators for 4% bandwidth for the passband frequency range between 18.6 and 19.4 GHz. The filters were designed with 300 nm tunable ferroelectric thin films. The design of the 2 pole filters has been described elsewhere.^[6,7] The filter was optimized using Sonnet em[®] tools.^[8] The geometry of the two pole filter is shown in Fig. 1. The filter has radial bias stubs for dc biasing of each resonator section. The input and output microstrip lines were biased using custom made bias stubs.^[9] Although

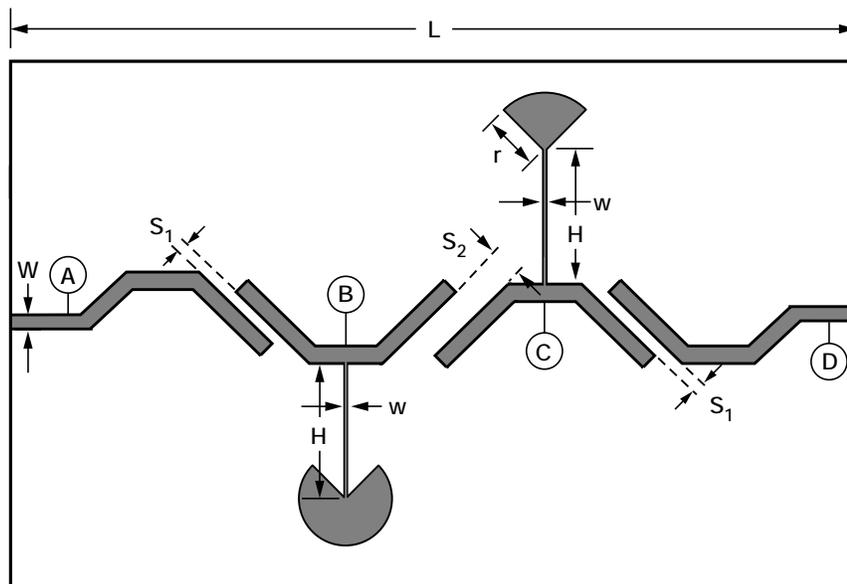


FIGURE 1. Geometry of the 2 pole microstrip tunable filter using the conductor/ferroelectric/dielectric multilayer configuration. The dimensions are $W = 86.25 \mu\text{m}$, $w = 12.5 \mu\text{m}$, $L = 6.8 \text{ mm}$, $H = 1.33 \text{ mm}$, $r = 200 \mu\text{m}$, $S_1 = 100 \mu\text{m}$, and $S_2 = 300 \mu\text{m}$.

the design of the filters was primarily for STO ferroelectric, it is also valid for BSTO with lower tunable range of relative dielectric constant $\epsilon_{r\text{BSTO}}$. At present, the relative dielectric constant of STO ($\epsilon_{r\text{STO}}$) is typically tunable between 4000 and 300 at low temperatures below 77 K^[10] whereas $\epsilon_{r\text{BSTO}}$ is tunable between 2500 and 400 at room temperature.^[5] These values depend markedly upon growth conditions, film thickness, dopants, doping concentration, and temperature.

III. EXPERIMENTAL

The samples with BSTO thin film on LaAlO₃ (LAO) substrates ferroelectric were obtained from the University of Maryland. 300 nm thick BSTO thin films were deposited on LAO substrates by pulsed laser deposition technique. The K-band Au/BSTO/LAO bandpass filter circuits were fabricated using standard positive photoresist lithography. The filters were studied under different bias conditions: (1) unipolar bias (UPB) where alternate nodes were biased positive, and ground, (2) partial bipolar bias (PBB) where input and output lines were grounded, and the resonator sections biased positive and negative alternatively, (3) full bipolar bias (FBB) where alternate sections (including the input and output lines) were biased positive and negative. It is important to note that the effective dielectric constant of the microstrip structure depends upon the electric field between the biased microstrip lines as well as the perpendicular field between the top conductor and the ground plane. The BSTO ferroelectric based filters were studied at room temperature and under vacuum, to eliminate any possibility of arcing at high bias voltages. Bias voltages were applied up to $\pm 400\text{V}$, with minimal power consumption. As can be seen in Fig. 1, the smallest spacing is between the input and output coupled sections. The maximum electric field will be across these two coupled sections compared to the coupled sections between the resonators. Swept frequency scattering parameter measurements were performed using an HP8510C automatic network analyzer (ANA).

IV. RESULTS

The swept frequency scattering parameter measurements performed on one of the gold/BSTO/LAO based K-band microstrip bandpass filter is shown in Fig. 2. The measurements were performed at room tempera-

ture with no bias. The minimum insertion loss of the filter has a minimum of 6.9 dB, which is primarily due to the higher loss tangent ($\tan\delta$) in BSTO thin films in the range of 0.01-0.1 at room temperature.^[5] The bias dependent frequency tunability of the filter measured at room temperature for (a) partial bipolar and (b) full bipolar configuration are shown in Fig. 3. As seen in the figures, the partial bipolar configuration is definitely improving the insertion loss of the filter, whereas the full bipolar configuration maintains the passband flat, with minimal ripple. In general, the full bipolar configuration gives the largest frequency tunability

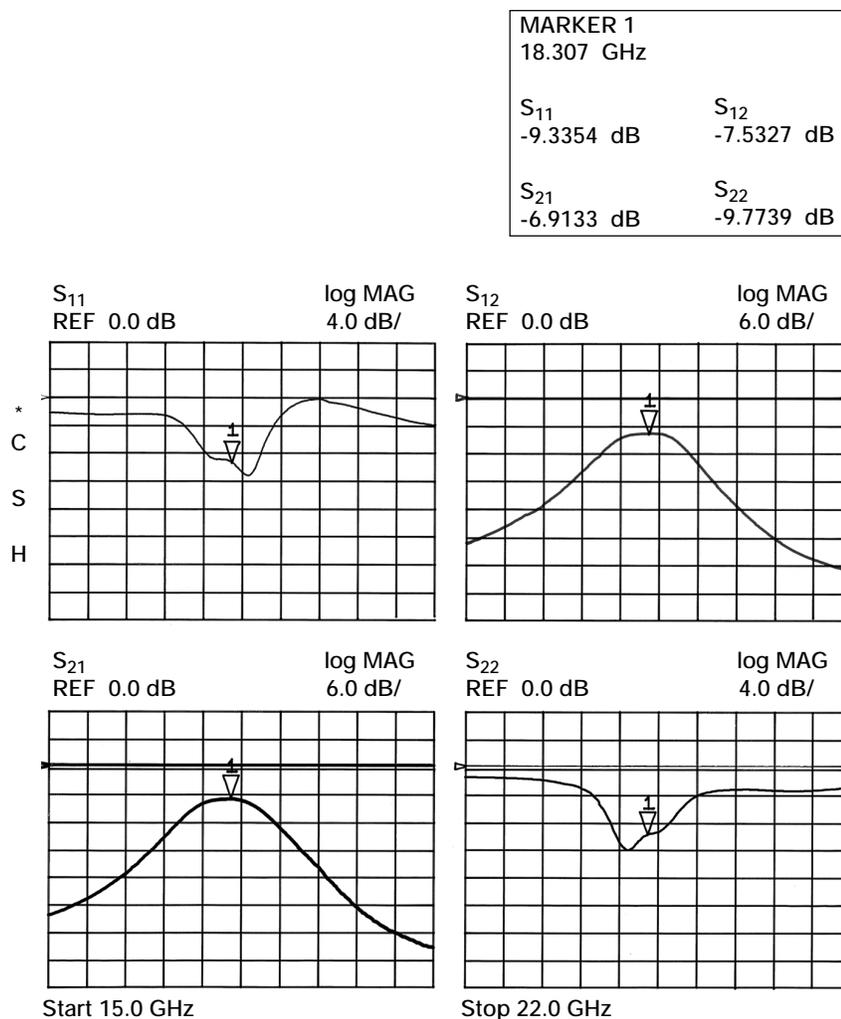


FIGURE 2. The swept frequency s-parameter measurements performed on a Au/BSTO/LAO filter at room temperature.

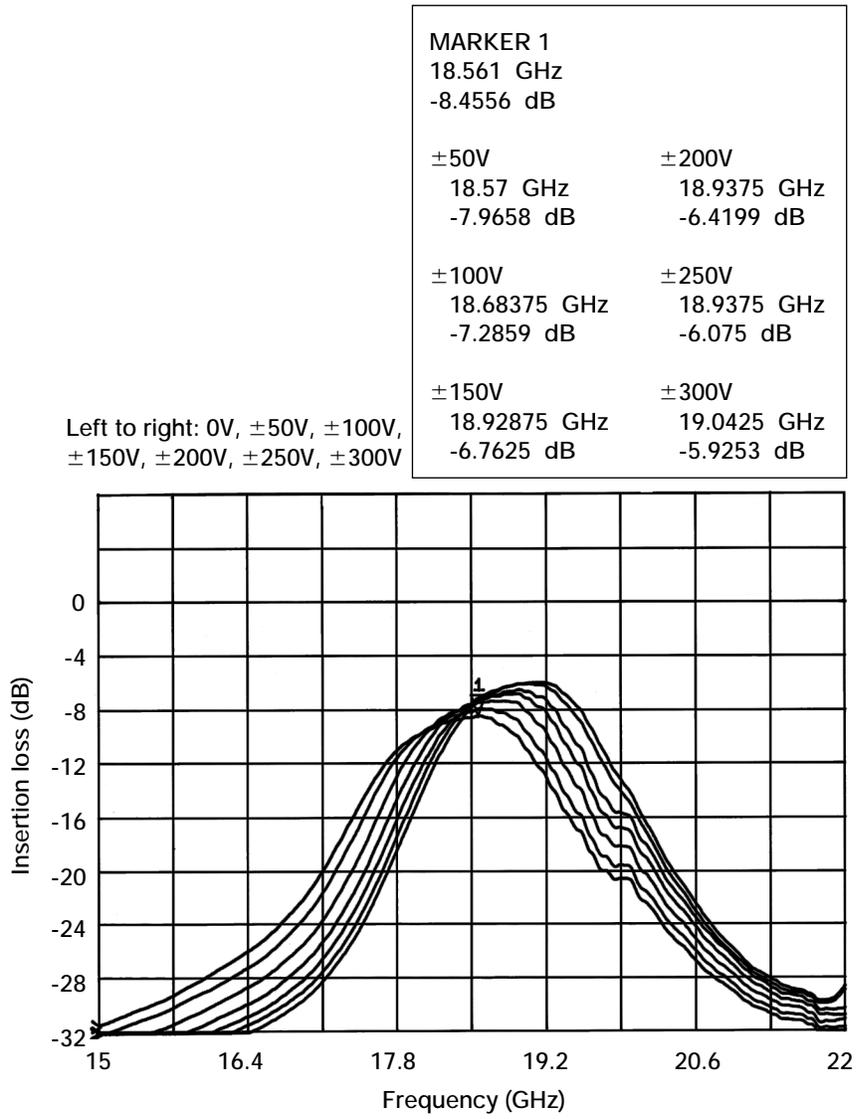


FIGURE 3a. The bias dependence of the same BSTO filter for a partial bipolar configuration.

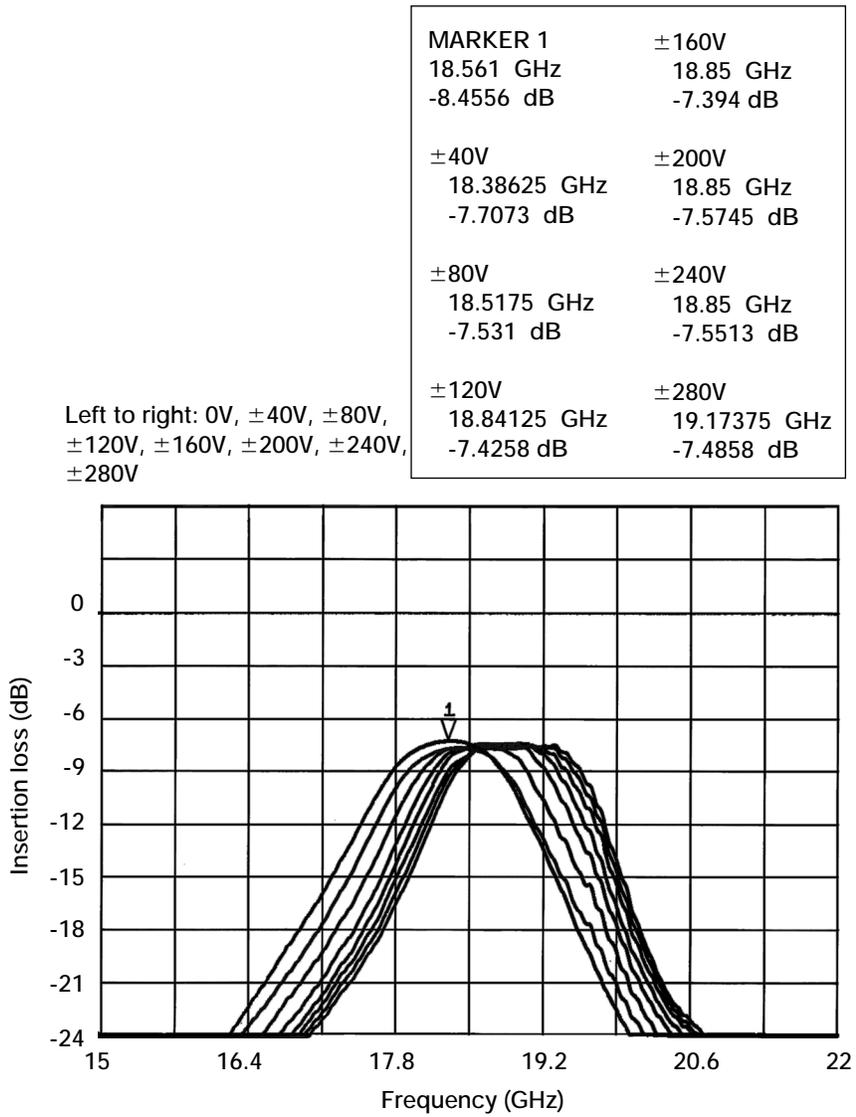


FIGURE 3b. The bias dependence of the same BSTO filter for a full bipolar configuration.

due to higher electric fields that can be applied in this configuration, and the partial bipolar gives the lowest insertion loss in the passband in the Au/BSTO/LAO filters. The center frequency versus E_{peak} is shown in Fig. 4 for the same filter. One can obtain the sensitivity parameter as the slope of the center frequency versus E_{peak} characteristics. It is evident that there are three distinct regions (8-16, 20-36, and 42-56 kV/cm) where the slopes of the characteristics are changing with the magnitude of the E_{peak} . There appears to be a threshold E_{peak} necessary, approximately 4 kV/cm, before the tunability is more pronounced. Also, between the three regions identified above, there appears to be transition regions. The origin for these transition regions is still under investigation. For the filter under discussion, the sensitivity parameter is approximately 15 MHz/cm/kV at fields between 8-16 kV/cm and reduces to 5 MHz/cm/kV at fields above 44 kV/cm, for measurements taken at room temperature. For comparison, the sensitivity parameter varies from 31 to 15 MHz/cm/kV for (gold, HTS)/STO/LAO based filters at 77 K and is greater than 100 MHz/cm/kV at 24 K for fields below 20 kV/cm. In general, we have observed that the sensitivity parameter is the highest at electric fields below 20 kV/cm in most samples tested to date.

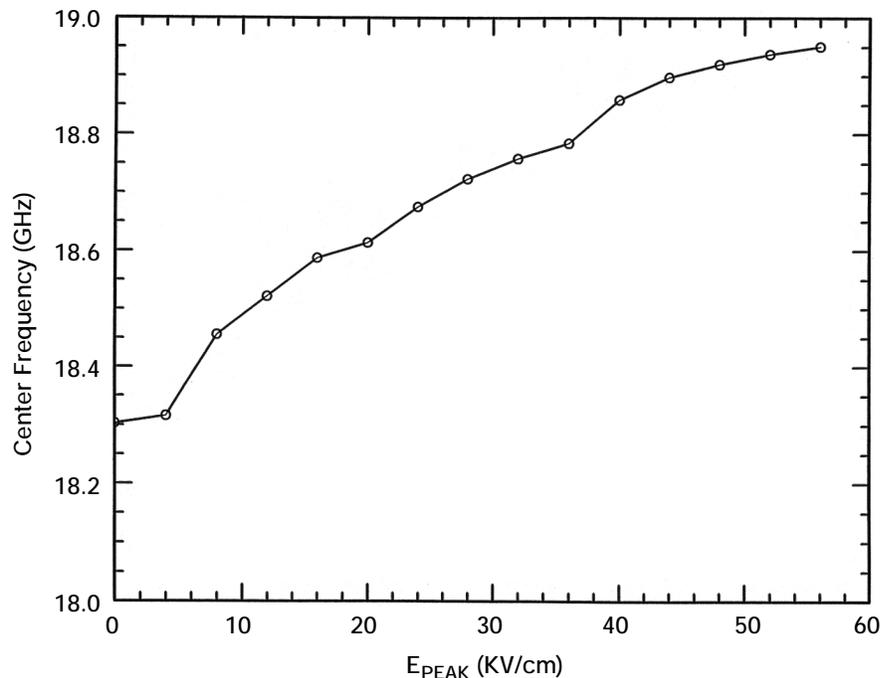


FIGURE 4. The electric field dependence of the center frequency of the filter for the full bipolar configuration.

Figure 5 shows the insertion loss and return loss versus E_{peak} for one of the Au/BSTO/LAO tunable filters tested at room temperature, using the partial bipolar bias configuration. We define the loss parameter as the slope of the insertion loss versus E_{peak} characteristics. What is evident from the figure is that there are two regions one in which there is a large change in insertion loss, greater than 0.6 dB (between 10 and 36 kV/cm) and the other in which the insertion loss varies less than 0.1 dB, above 36 kV/cm. Depending upon the design requirements one could choose to operate in the region where the insertion loss variation is low or in a region where the insertion loss could be reduced to the lowest level possible. Note that the insertion loss remains a constant at fields above 36 kV/cm. The return loss on the other hand, decreases to its lowest value around 44 kV/cm. This result is contrary to conventional microstrip filters, as the insertion loss should be improving with lower return losses. Similar results have been observed in STO ferroelectric tunable filters as well. The reason for constant insertion loss with improving return loss could possibly be due to additional losses in the ferroelectric thin film at these high fields. As can be seen from Figs. 4 and 5, large tunability at low fields below 20 kV/cm does not necessarily give the lowest insertion

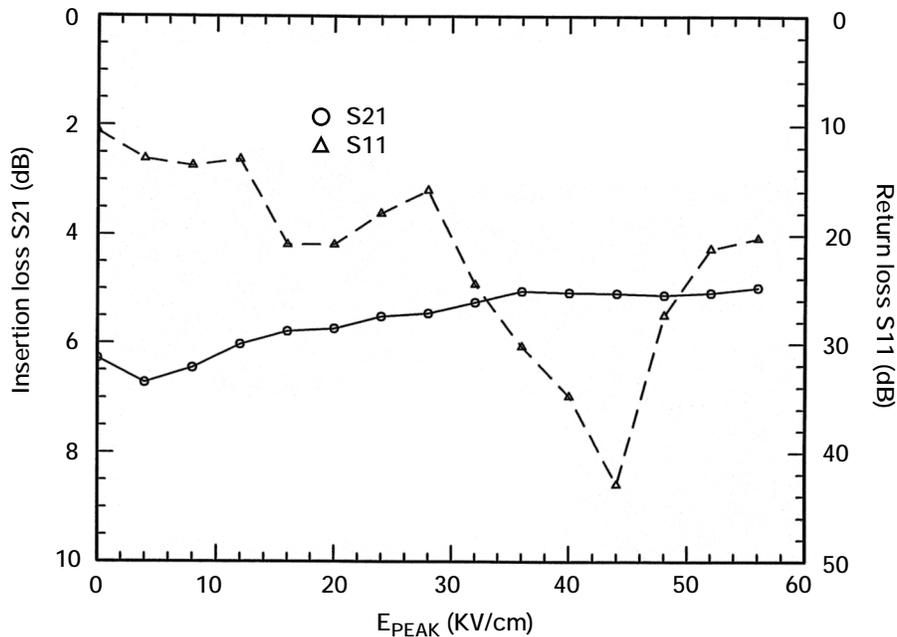


FIGURE 5. The electric field dependence of the insertion loss and return loss for the same filter, measured at room temperature under the partial bipolar bias configuration. The full bipolar configuration maintains the passband insertion loss almost constant throughout the tuning range, as in figure 3b.

loss for the filters. The loss factor varies from -0.02 dB/cm/kV at fields below 20 kV/cm to -0.005 dB/cm/kV at high fields above 40 kV/cm. It is evident from Fig. 5 that the return loss is below -20 dB between 30 and 50 kV/cm of E_{peak} . Figure 6 shows the electric field dependence of bandwidth for the same BSTO based 2 pole filter. The bandwidth reduces from 1350 MHz (7%) to approximately 1200 MHz (6%) at low fields below 20 kV/cm and increases to approximately 1500 MHz (8%) at higher fields. The BSTO based filters allow a frequency tunability of approximately 200 to 300 MHz below 20 kV/cm at room temperature, a factor of 5 smaller than the best STO based filter circuit operating at 77K.^[7]

V. DISCUSSIONS

A critical finding from this work, one which we believe will have an impact on the use of ferroelectric thin films in tunable filters is that the sensitivity parameter remains almost the same for each sample, irrespec-

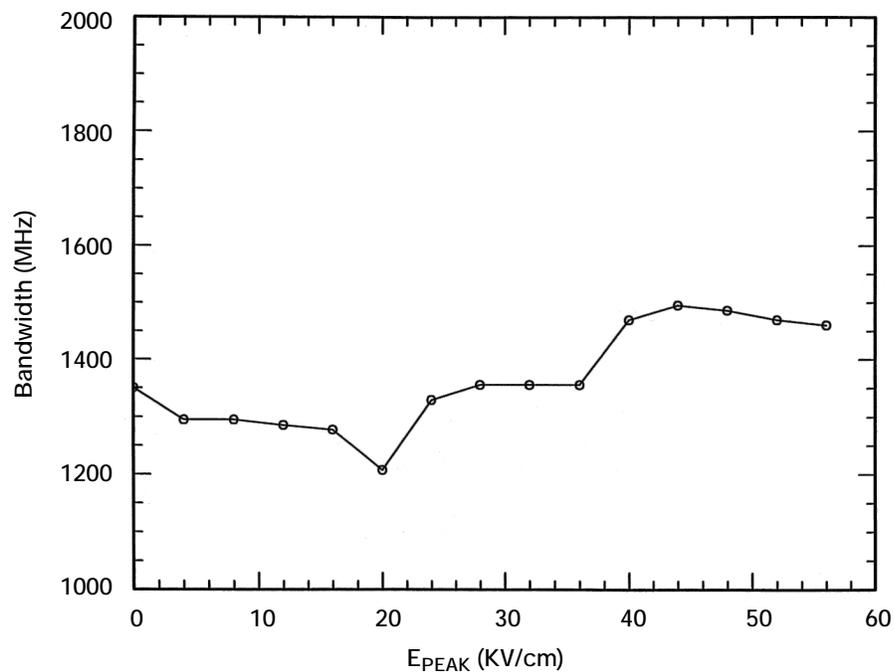


FIGURE 6. The electric field dependence of the passband bandwidth of the same filter at room temperature under the full bipolar bias configuration.

tive of the bias configuration employed. Figure 7 shows the frequency shift versus E_{peak} for two different samples. Remarkably, the sensitivity parameter remains very much the same at low fields below 20 kV/cm for the three different bias configurations defined earlier in this paper. This is a significant result since evaluation of the ferroelectric materials can be accomplished using the sensitivity parameter and the loss parameter, when used in tunable microstrip filters. Ideally, a ferroelectric material should yield a low loss parameter and a high sensitive parameter, for highly reliable tunable filters. As shown in Fig. 7, the sensitivity parameter of sample 1 is higher than that of sample 2.

For the practical applicability of these filters, the manufacturers should give the typical values of low field (≤ 20 kV/cm) and high field (>20 kV/cm) sensitivity parameters, and loss parameters. In addition, the typical electric field or bias voltage dependence of the important parameters such as the center frequency, minimum insertion loss in the passband, return loss, the passband ripple, and bandwidth of the filter will allow the users to choose the optimum filter's response based on the design requirements.

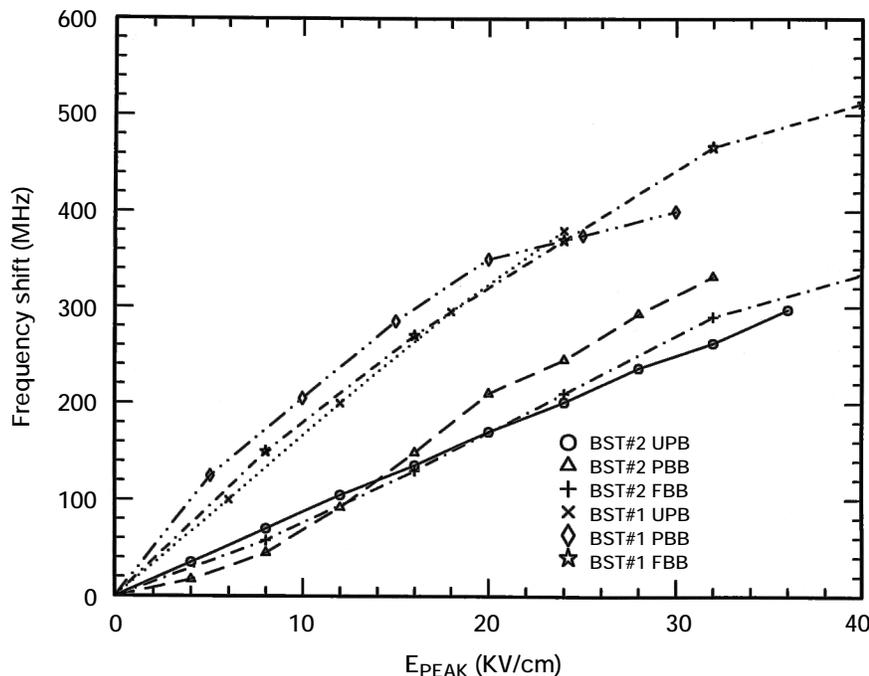


FIGURE 7. The electric field dependence of the frequency shift in two different samples of Au/BSTO/LAO filters. The sensitivity parameter in sample 1 is higher than the sensitivity parameter in sample 2.

VI. SUMMARY AND CONCLUSIONS

Room temperature tunable BSTO ferroelectric based microstrip filters using the Au/BSTO/LAO configuration have been fabricated and tested using different bias configurations. The correlation of electric field with the important design parameters such as the insertion loss, return loss, center frequency, and the bandwidth of the filters were studied. Based on our study, we propose two new parameters, which may be important for the applicability of the ferroelectric tunable filters. The sensitivity parameter is defined as the incremental change in the center frequency for incremental change in E_{peak} . The sensitivity parameter varies between 15 and 5 MHz/cm/kV at room temperature, with largest sensitivity parameters observed below 20 kV/cm, typically. The loss parameter is defined as the incremental/decremental change in the insertion loss for incremental change in E_{peak} . The loss parameter varies from -0.02 dB/cm/kV at fields below 20 kV/cm to -0.005 dB/cm/kV at high fields above 40 kV/cm.

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