Ferroelectric Thin-film Based Electrically Tunable Ku-band Coplanar Waveguide Components

Guru Subramanyam[1], Nazme Mohsina[1], Abdullah Al Zaman[1], Félix Miranda[2], Fred Van Keuls[2], Robert Romanofsky[2], and Joseph Warner[2]

[1]Dept. of ECE, University of Dayton, 300 College Park, Dayton, OH 45469-0226
[2]NASA Glenn Research Center, Cleveland, OH 44135

Abstract **Barium strontium titanate ($Ba_{0.6}Sr_{0.4}TiO_3$) thin-film based tunable coplanar waveguide (CPW) components were studied in this research. The CPW components modeled and experimentally verified include CPW transmission lines, resonators and 2-pole filters. The resonators and filters fabricated and tested exhibited a frequency tunability of approximately 3% for a bipolar bias voltage of ±100V, corresponding to a peak biasing field of 40 kV/cm.**

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 higher power, smaller size, lighter weight, lower cost frequency agile components [1-3]. Examples of applications in the area of microwave engineering include field-dependent varactors, tunable resonators, phase shifters, and frequency-agile filters [1-3]. Frequency and phase agility in these circuits is achieved through the ferroelectric thin-film's relative dielectric constant (ε_{rFE}) nonlinear response to an applied dc electric field. In this study we focus on $Ba_{0.6}Sr_{0.4}TiO_3$ (henceforth BSTO) ferroelectric thin-film based frequency agile CPW components such as resonators and filters. BSTO (60/40) has a Curie Temperature (T_c) of 290K, ideal for room temperature tunable components.

In our approach, the tunable CPW components were realized using a conductor/ferroelectric/dielectric configuration. The cross-sections of the CPW transmission lines modeled are shown in figure 1, along with the tunable microstrip structure. These structures consist of a dielectric substrate (typically lanthanum aluminate (LAO), 254 μm thick), a BSTO ferroelectric thin-film layer (thickness 't' modeled for t=300-2000 nm), a 2 μm thick gold thin-film for the conductor. The important geometrical dimensions are indicated in the figure. W is the width of the center conductor, and S is the spacing between the center conductor and the ground lines. The critical design parameters for the tunable circuits, i.e., characteristic impedance (Z_0), and effective dielectric constant (ε_{eff}) are functions of the electric field dependent ε_{rFE} and tanδ of the ferroelectric thin-film.

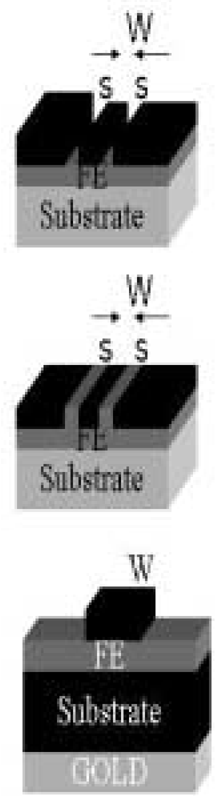

Figure 1. Ferroelectric tunable CPW, ferroelectric filled CPW and microstrip for frequency agile components.

Filling the air-gap between the center conductor and the ground-lines results in a ferroelectric filled CPW structure (FFCPW). Comparing the effective dielectric constant of the CPW line shown above with a FFCPW line and a ferroelectric tunable microstrip line for the same ferroelectric properties, we found that the FFCPW offers

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much larger tunabilities, due to improved filling factor. Figure 2 shows the change in effective dielectric constant for the three structures, at a specific frequency of 20 GHz. As one can see, the FFCPW has almost twice the change in ε_{eff} compared to the CPW, indicating that one could obtain higher tunabilility at a lower dc biasing electric field. The FFCPW has almost three times higher tunability compared to the tunable microstrip line. In this study, we focus on the CPW structure shown in figure 1, for the resonators and filters.

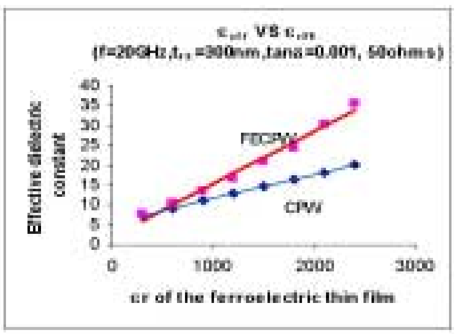

Fig.2. Comparison of the effective dielectric constant versus ε_{rFE} for a ferroelectric filled CPW, and ferroelectric filled CPW (FFCPW) on a 12 mil thick MgO substrate.

II. DESIGN

The ferroelectric tunable CPW resonators and filters were designed such that individual sections could be biased separately using bias stubs, for improved tunability. Half wavelength resonators were capacitively coupled to the input and output sections as shown in figure 3. The input and output sections were designed for 50 ohms where as the inner resonator sections were designed for 75 ohms. This is due to higher tunabilities for higher characteristic impedances. The dc electric field applied between the sections, as well as between the conductor and the ground lines are responsible for dielectric tunability of the ferroelectric thin-film.

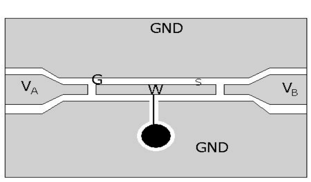

Fig.3.a.

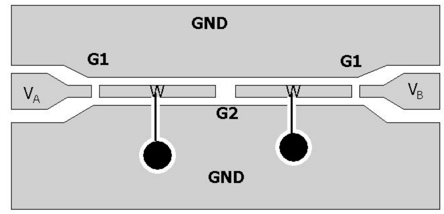

Fig.3.b.

Fig.3. Top view of the CPW resonator and filter with bias pads, on MgO substrate. Dimensions are the following: Length of the resonator sections: 160 mils, length of input and output coupled sections: 60 mils. W: width of the center conductor: 3.5 mils in the input and output sections, 2.5 mils in the resonator sections, s: Spacing between center conductor and the ground lines: 1 mil in the resonator sections. G, G1: 1 mil. G2=6 mils. Bias stub width: 1 mil. Bias stub pad diameter: 2 mils.

III. THEORETICAL MODELING

The theoretical modeling of the resonators and filters on MgO substrates was performed using Sonnet em. The ferroelectric thin-film was assumed to be dielectric tunable from ε_{rFE} of 1200 at zero-bias to 300 at a high bias, consistent with our measurements on CPW transmission lines. The filter was designed for 2% bandwidth centered around 16 GHz.

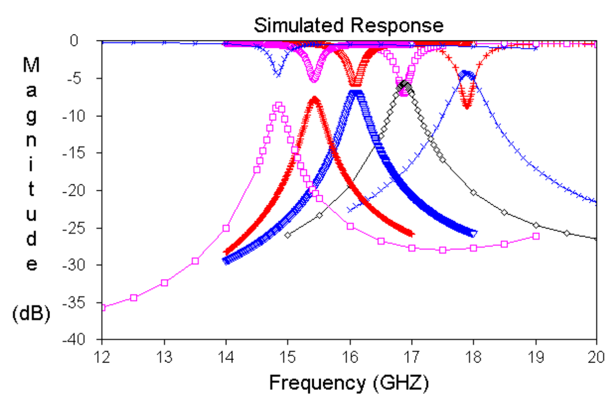

Fig.4. Simulated response for the 2-pole CPW filter for ε_{rFE} of 300 to 1200 (right to left) with an increment of 300. Tanδ of the ferroelectric film was assumed to be 0.01 (worst case).

As shown in the simulated response of figure 4, the CPW filter was tunable from a center frequency of 18 GHz at an ε_{rFE} of 300 to approximately 15 GHz at an ε_{rFE} of 1200. As one can notice, the reflection loss steadily increases as the ε_{rFE} increases.

IV. EXPERIMENTAL RESULTS

The CPW resonators and filters were fabricated on pulsed laser ablated BSTO thin-films (350 nm thick) on MgO substrates using standard positive photoresist lift-off photolithography technique. The samples were tested at room temperature and under vacuum (<50 mtorr) in a cryostat to diminish any possibility of arcing at high bias voltages. An on-wafer CPW probing system was used for the measurements, along with HP8510C network analyzer. Bias voltages up to ±200 V were applied to the ferroelectric tunable circuits with minimal power consumption (<2 mW). The biasing of the resonators and filters was done such that alternate sections of are biased to equal and opposite polarity voltages for large biasing electric fields. Such a configuration is called as the full bipolar biasing.

Figure 5 shows the frequency response of one of the CPW resonators tested. The insertion loss of the resonator was –4.79dB at zero bias, and the reflection loss of –12dB at a center frequency of 16.6 GHz. The insertion loss improved to –3.1dB at a unipolar bias of 350V (peak electric field of 140 kV/cm) at a center frequency of 16.87 GHz, a tunability of approximately 1.5% at room temperature. The loaded Q of the resonators was typically between 20 and 25. This is primarily due to large tanδ (~0.01) in the current BSTO films.

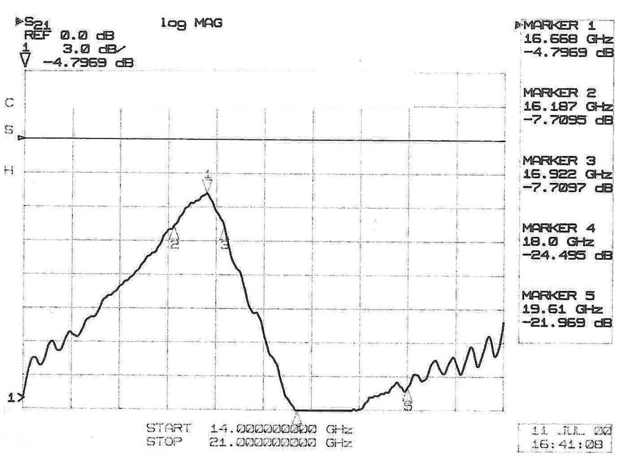

Fig.5. Frequency response of a CPW resonator at room temperature and zero-bias.

Figure 6 shows the frequency response of a CPW filter on MgO substrate tested at room temperature at zero-bias. The filter had a center frequency of 17.2 GHz, and a 3dB bandwidth of 500 MHz. The filter was tunable by approximately 3% at room temperature with bias voltages upto ±100V. Another tunable CPW 2-pole filter tested,

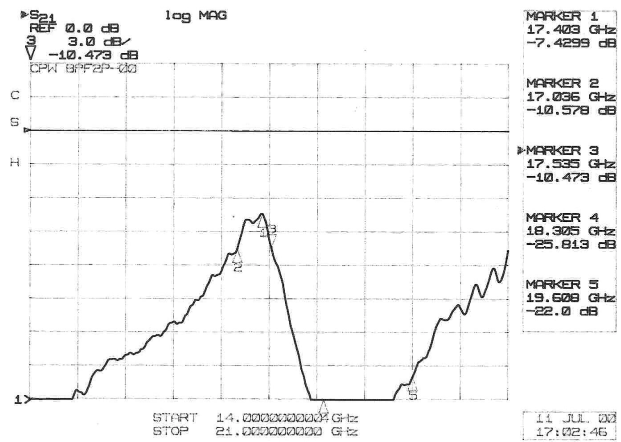

Fig.6. Frequency response of a tunable CPW 2-pole filter at zero bias and room temperature.

exhibited a tunability of close to 3% for an applied bipolar bias of ±100V (peak electric field of 40 kV/cm) as shown in figure 7. The insertion loss of the filter was –8.1 dB and the

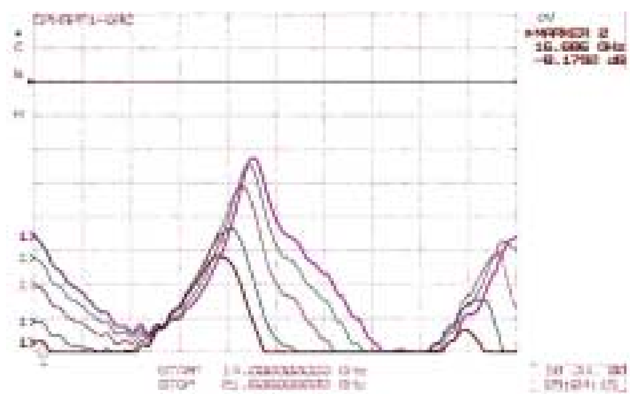

Fig.7. Frequency response of a CPW filter with bipolar biasing from 0V to ±100V in step of ±25V(left to right). Note that the insertion loss improves steadily with applied bias.

center frequency of 16.685 GHz at zero-bias. When biased by a full bipolar biasing scheme upto a peak electric field of 40 kV/cm, the insertion loss improved to –5.25 dB at the center frequency of 17.17 GHz. The improvement in insertion loss due to full bipolar biasing scheme has been observed in tunable microstrip filters as well[4].

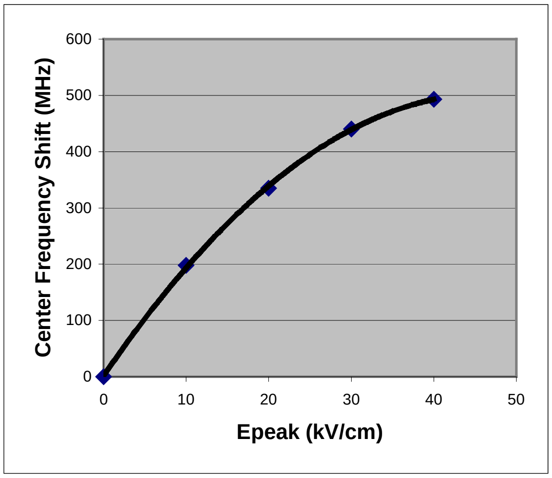

Fig.8.a.

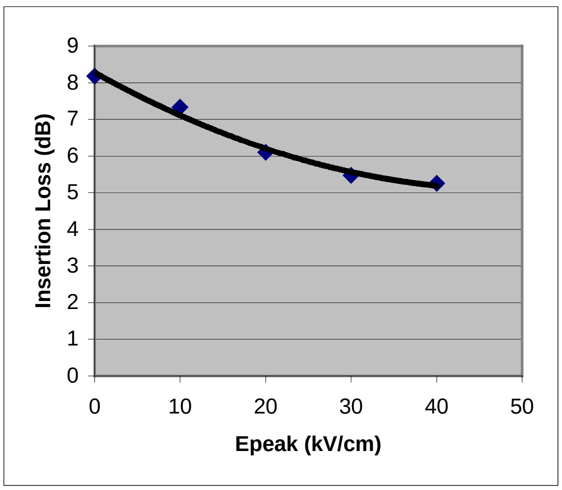

Fig.8.b.

Fig.8. The Center frequency shift vs Epeak and the insertion loss vs Epeak are plotted for the CPW filter in figure 7.

The peak electric field (E_{peak}) is the dc electric field between the center conductor and the ground lines, the dominant field influencing the ferroelectric material. In an earlier study, we had discussed the geometry independent parameters sensitivity and loss-parameters [4]. The sensitivity parameter is the slope of the center frequency shift vs E_{peak}, and the loss-parameter is the slope of the insertion loss vs E_{peak}[4]. One would like to have a large sensitivity parameter at the same time improving the insertion loss of the filter, resulting in a negative loss-parameter.

The center frequency shift versus the peak electric field is shown in figure 8 for the same filter in figure 7. The sensitivity parameter is approximately 20 MHz /(kV/cm) at E_{peak} below 20 kV/cm. In comparison, BSTO based microstrip tunable filter had a sensitivity parameter of 15 MHz/(kV/cm) at low fields. The figure 8.b. shows the insertion loss vs E_{peak} for the same filter in figure 7. The loss-parameter was calculated to be approximately –0.124 dB/(kV/cm) at low fields below 20 kV/cm, compared to –0.02 dB/(kV/cm) in the BSTO tunable microstrip filter.

V. SUMMARY

In summary, ferroelectric thin-film tunable CPW components have been studied in this research. Our study included modeling and experimental verification of tunable CPW transmission lines, resonators and filters. The ferroelectric tunable CPW filters were tunable by more than 3% at bias voltage levels of ±100V. The BSTO based CPW filters offer higher sensitivity parameter as well as lower loss parameter compared to BSTO tunable 2-pole microstrip filters.

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