Tunable RF Filters Using Thin Film Barium Strontium Titanate Based Capacitors

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***Abstract* — Tunable lowpass and bandpass filters based on barium strontium titanate (BST) capacitors are reported. For the lowpass filter, 40% tunability was achieved at 9V. Intermodulation distortion generated by the lowpass filters was also measured and predicted using a nonlinear model for the BST capacitors. The bandpass filter showed 45% tunability with an applied DC bias of 10 V.**

I. INTRODUCTION

Strontium titanate, $SrTiO_3$, (STO) and barium strontium titanate, $(Ba_x, Sr_{1-x})TiO_3$, (BST) are two of the most popular ferroelectric films currently being studied for the design of tunable RF components. Depending upon the specific composition and temperature, BST can exhibit ferroelectric or paraelectric behavior. The permittivity of paraelectric BST (or STO) can be controlled by the application of a DC electric field. By exploiting this property of BST (or STO), tunable capacitors (varactors) can be fabricated. In parallel plate capacitors, tunabilities greater than 50% are achievable at DC bias levels as low as 2-5 Volts [1]. Other advantages of BST capacitors include the ease of integration with active devices such as MMICs, low cost simultaneous fabrication of multiple parts, low losses in high quality films, and minimal frequency dispersion. In addition, tunable BST capacitors do not produce junction noise (as compared to varactor diodes), and due to the high dielectric constant of BST thin films (typically around 300) [2], very high energy density capacitors can be fabricated on appropriately buffered Si substrates.

A voltage controlled capacitor is one of the core components in tunable RF and microwave devices such as voltage controlled oscillators (VCO), tunable filters, phase shifters, and tunable matching networks. Tunable filters are widely used in military applications and satellite communication systems as receiver front-ends. Most of today's tunable filters rely on either mechanical tuning or switched capacitor filter banks. Mechanically tunable filters have high power handling capabilities with a low insertion loss. The main disadvantages of these filters are low tuning speeds, large size, and large mass. Varactor diode based tunable filters are much faster, but they suffer from high losses at RF and microwave frequencies [3]-[4]. Currently, switched capacitor filter banks are widely used, but they do not have a continuous tuning range. Ferroelectric materials have the potential to be used in the design of low loss tunable filters with fast tuning speeds.

STO thin films have been intensively studied in recent years for possible applications in tunable filters [5]. Tunable STO characteristics can be obtained at significantly low temperatures (~77K), thus allowing the use of high temperature superconductors (HTS). Planar microstrip HTS tunable filters are currently being tested by the wireless industry for receiver front-end systems [6]. However, these systems are very expensive and require tuning voltages of several hundred volts. Furthermore, since STO thin films exhibit very little tunability at room temperature (curie temperature, $T_C \leq 0$ K), they cannot be integrated with systems operating at room temperature. BST thin films can overcome these difficulties. Depending on the specific composition, BST can be made tunable at room temperature. With the recent advances in BST film deposition and processing, lower insertion loss tunable filters requiring lower drive voltages can be fabricated.

In this paper, design, fabrication and measurement results for tunable lowpass and bandpass filters based on parallel plate BST capacitors are presented. Intermodulation distortion measurement results for the low pass filters as well as their predicted values from simulations are also reported.

II. FABRICATION OF THE BST CAPACITORS

Parallel plate capacitors were fabricated on 500 µm thick silicon wafers covered with approximately 500 Å of thermal SiO_2 and a final 1000 Å of Pt (this Pt layer acts as the device ground plane). Metalorganic chemical vapor

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deposition (MOCVD) technique was used to grow 3000 Å thick $(Ba_{0.7}Sr_{0.3})TiO_3$ thin films. MOCVD is the deposition method of choice for the fabrication of BST thin films. It provides excellent composition control, large area coverage, and the potential for areal homogeneity and conformal coating of complicated topography [7]-[8]. In this work, all BST films were uniformly deposited on 150 mm wafers, thus indicating the suitability for commercial mass production. Top electrodes completing the parallel plate capacitor structures were deposited by either sputtering or electron-beam evaporation. Using standard photolithographic methods and reactive ion etching, the top platinum surface was patterned. The capacitance vs. voltage curve for a typical BST capacitor used in this work is shown in Fig.1.

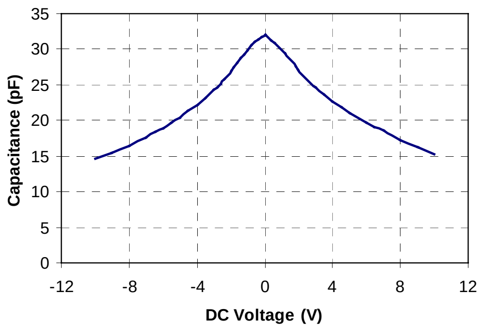


Fig. 1. The C-V curve of a typical BST capacitor.

III. Fabrication and Measurement of Lowpass and Bandpass Filters

A. Tunable Lowpass Filter

A lumped element tunable lowpass filter (LPF) based on the 3rd order 0.5 dB ripple Chebychev prototype was designed as shown in Fig. 2. To the best of our knowledge, this is the first demonstration of a BST capacitor based lumped element tunable lowpass filter.

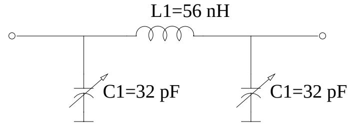
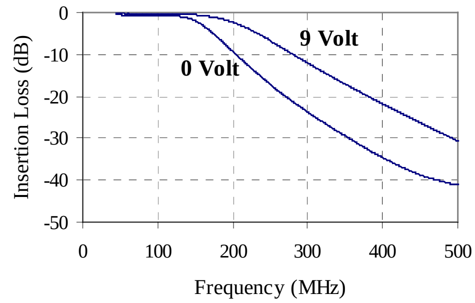


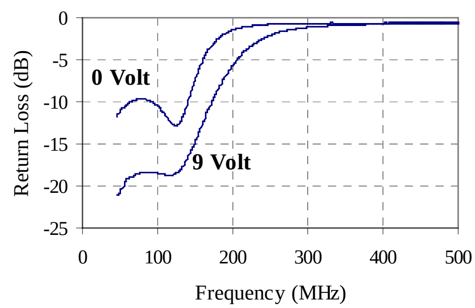
Fig. 2. The circuit schematics of the 3rd order LPF.

The fabricated lowpass filter was measured with an HP8510C vector network analyzer. The insertion loss and the return loss of the filter can be seen in Fig. 3a and Fig. 3b, respectively.

The measurement results show that the 3 dB cut-off frequency can be tuned from 160 MHz to 210 MHz by biasing the capacitors at 9 V, giving 30 % tunability. The maximum measured insertion loss in the passband was 0.8 dB, and for all biasing conditions, the passband return loss was higher than 10 dB. By comparing the measured and simulated responses of the filter, the quality factor of the 32 pF BST capacitors was determined to be 50 at 160 MHz. The capacitance decreased by a factor of 1.8 with the application of 9 V. The quality factor of this BST capacitor is already better than commercially available varactor diodes of similar capacitance.



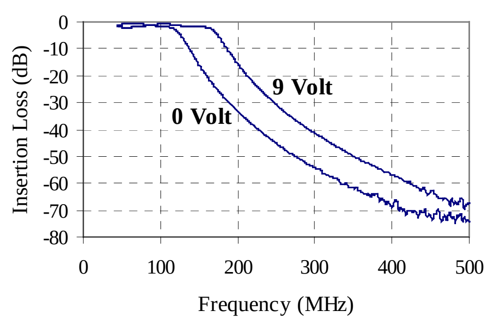
(a)



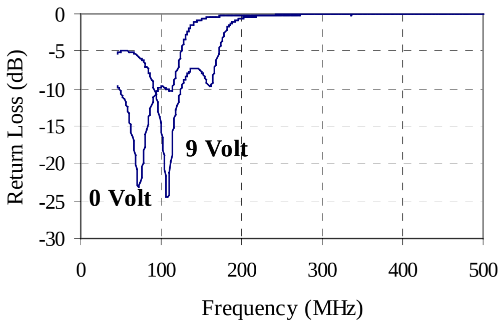
(b)

Fig. 3. (a) The insertion loss and (b) the return loss of the 3rd order lowpass filter with changing the DC bias voltage.

For sharper stopband attenuation, a 5th order tunable lowpass filter was fabricated. The measured insertion loss and the return loss of this filter are shown in Fig. 4a and Fig. 4b, respectively. The results show that the 3 dB cut-off frequency can be tuned from 120 MHz to 170 MHz, resulting in 40 % tunability.



(a)



(b)

Fig. 4. (a) The insertion loss and (b) the return loss of the 5th order lowpass filter with changing the DC bias voltage.

A nonlinear circuit model as shown in Fig. 5 was developed to predict the intermodulation distortion generated by the filters. The nonlinear capacitor and the leakage resistor accounting for the dielectric loss were represented by 5th order polynomials fitted to the measured C-V and R_P-V curves for the device. In this model, R_S accounts for the conductor losses in the BST capacitor.

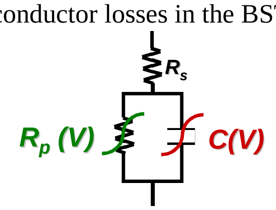


Fig. 5. The nonlinear model of the BST capacitors.

The 3rd order intercept points (IP3) were measured using a two-tone test setup. The output IP3 point of the 3rd and 5th order lowpass filters were measured to be 24 dBm and 22 dBm at 0 V bias, respectively. Using the nonlinear model developed, the IP3 points were predicted to be 29 dBm and 25 dBm, respectively. When the nonlinear resistor is not incorporated in the circuit model, a reasonable agreement between simulations and measurements cannot be achieved. Therefore, to improve the IP3, the nonlinearity of the leakage resistance can be considered as a design parameter while optimizing thin film BST for losses. By reducing the BST losses, one should be able to improve the IMD performance. By applying a small DC bias, one can substantially increase the IP3 point at the expense of reducing the tunability.

B. Preliminary Results for a Tunable Bandpass Filter

A similar approach was followed to design and fabricate a tunable bandpass filter (BPF). The circuit schematics of a lumped element tunable bandpass filter is shown in Fig.6.

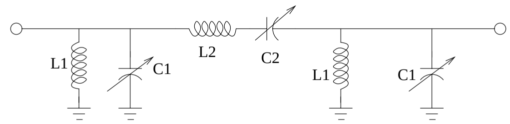


Fig. 6. Schematics of a 3rd order tunable BPF.

Using J-inverters, the series LC circuit in Fig. 6 was converted to a parallel LC circuit [9], which is easier to fabricate. Note that the shunt inductors provide a DC short to the ground, thus making it impossible to apply the tuning DC bias to the filter. A possible solution is to connect a large capacitor in series with the shunt inductors, preventing them from shorting the DC tuning voltage. The complete circuit for the designed filter can be seen in Fig. 7. The BPF was designed with the component values; L=47 nH, L_{11}=11 nH, L_{22}=15 nH, and C_{11}=C_{22}=135 pF, and C=3.3 nF. The measurement results for this bandpass filter are shown in Fig. 8.

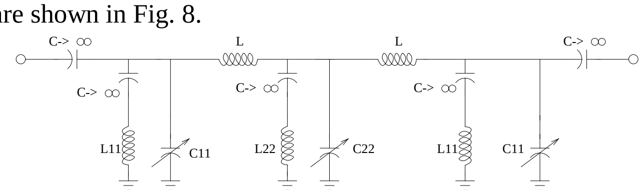
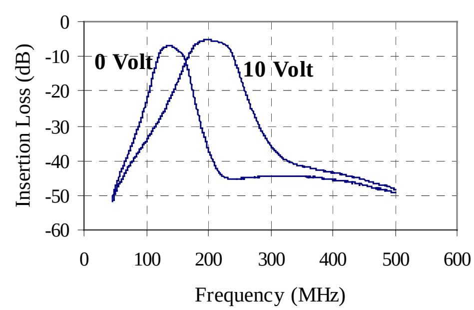
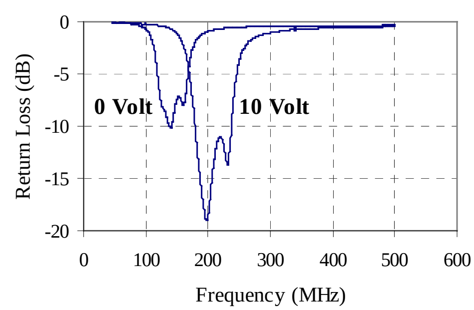


Fig. 7. The complete circuit of the tunable bandpass filter.



(a)



(b)

Fig. 8. (a) The insertion loss and (b) the return loss of the measured bandpass filter with changing the DC bias voltage.

The results show that the center frequency of the BPF can be tuned from 140 MHz to 200 MHz, corresponding to 45 % tunability with the application of 10 V. The insertion loss in the passband was 7 dB at 0 V, which reduced to 5.1 dB with the application of 10 V. The minimum passband return losses were 7.2 dB at 0 V and 11.5 dB at 10 V. By comparing the measured and simulated responses of the filter, it was determined that the 135 pF BST capacitors had a quality factor of 26 at 150 MHz. This indicates that of the 7 dB insertion loss measured at 0 V, only 2.5 dB was directly attributable to the BST capacitors. The remainder of the insertion loss (4.5 dB) is mostly due to the low quality factor of the inductors used. Higher quality factor capacitors with thicker metallization have been fabricated and we are in the process of incorporating these capacitors in the BPF to improve its insertion loss.

IV. Conclusion

In summary, tunable lowpass and bandpass filters based on parallel plate BST capacitors were reported. 40 % tunability for the lowpass filter was achieved at 9V. The quality factor of the 32 pF BST capacitors used in the LPFs was determined to be 50 at 160 MHz. The bandpass filter showed 45% tunability with an applied DC bias of 10 V. The insertion loss of the bandpass filter was measured to be 7 dB, which was primarily due to the low quality factor of the inductors used. The quality factor of the 135 pF BST capacitors used in the BPF was determined to be 26 at 150 MHz. This represents an improvement when compared to varactor diodes having similar capacitance values measured at similar frequencies. With the recent advances in BST film deposition and processing, it will be possible to obtain tunable filters with improved insertion loss performance.

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