# Discrete Barium Strontium Titanate (BST) Thin-Film Interdigital Varactors on Alumina: Design, Fabrication, Characterization, and Applications

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***Abstract* — Discrete Barium Strontium Titanate (BST) thin-film capacitors in industry standard 0603 footprint are introduced and characterized. BST capacitors have a voltage-dependent permittivity, enabling BST thin-film capacitors to be used as tuning elements in frequency agile devices. The capacitance changed by 1.5:1 at 35 V (116 kV/cm) bias. The temperature dependence of the capacitance was measured to be less than ± 20 % from − 100 °C to +100 °C. A 2nd-order tunable combline bandpass filter on FR4 substrate has been implemented using the discrete BST varactors. The filter showed a center frequency tuning of 22% from 2.14 GHz to 2.61 GHz upon application of 130 V (433 kV/cm) bias. The zero-bias insertion loss was 4.9 dB which decreased to 2.9 dB at the high bias state. The return loss was better than 11 dB over the tuning range. Nonlinear characterization of the filter using two-tone test and a digitally-modulated CDMA 2000 signal showed an IP3 of +32 dBm and an ACPR of better than − 50 dBc up to 26 dBm of input power, respectively.**

***Index Terms* — Discrete, varactors, capacitors, BST, ferroelectric, thin-film, barium strontium titanate, bandpass filter, IP3, ACPR, temperature-dependence.**

## I. INTRODUCTION

Ferroelectric varactors have been extensively investigated as tuning elements for frequency agile devices. Tunable filters [1]–[5], phase shifters and matching networks have been reported in the literature. BST varactors are used in two main embodiments, either as a metal-insulator-metal (MIM) capacitor or as a planar interdigital (IDC) capacitor. We have previously focused on BST thin-film interdigital varactors on sapphire and alumina and reported tunable filters monolithically integrated with the BST varactors [1], [2]. These filter had insertion loss in the 3–7 dB range over the full tuning range. A significant contribution to the total insertion loss was identified as skin effect loss in transmission lines used for the filter structure. This is especially significant in the frequency range of 1–6 GHz where the lithographic challenge is fabricating interdigital fingers that are 5 $\mu$m (three skin depths) thick and spaced 3–4 $\mu$m apart. One solution to this problem is to fabricate discrete BST thin-film interdigital varactors and subsequently integrate them in a hybrid manner on a microwave laminate. This enables the transmission lines comprising the filter to be considerably thicker than three skin depths at the frequencies of interest and simultaneously affording a simple and inexpensive integration with BST thin-film varactors. This solution compares favorably with the one where a masking process is employed to increase the metal thickness for the transmission lines in the circuit to greater than that used for the fingers in the interdigital varactors. This masking process is essential for avoiding aspect ratio problems during photolithography and lift-off.

We report discrete BST thin-film interdigital capacitors on alumina. The capacitors were fabricated on a 1 inch square tile of alumina comprising approximately 150 capacitors of 0603 (60 mils X 30 mils) footprint. The singulation was done using a diamond saw. We report the electrical and thermal characterization of the BST varactors in discrete form and also demonstrate a tunable combline filter on a FR4 board using the discrete varactors. Tuning data and nonlinear characterization of the filter is also presented.

## II. BST INTERDIGITAL VARACTOR DESIGN AND CHARACTERIZATION

In this work we have chosen polycrystalline alumina ($Al_2O_3$) as the substrate for fabrication of the BST varactors. Alumina is an excellent substrate for frequency-agile devices since it exhibits low loss tangent ($\sim 10^{-4}$) in the microwave range. It is also low cost when compared to fabrication on single crystal substrates conventionally used such as MgO, $LaAlO_3$, and $Al_2O_3$ (sapphire). ($Ba_{0.6}Sr_{0.4}$) $TiO_3$ thin-films were deposited on double side polished alumina substrate (Coorstek, Golden, Colorado) using a radio frequency magnetron sputtering technique. A deposition time of 60 minutes resulted in a film thickness of 0.6 $\mu$m. Post deposition anneal was done *ex-situ* in air at 900 °C for 20 hours to fully crystallize and densify the BST films. Detailed deposition conditions are described elsewhere [6].

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An array of discrete IDCs was patterned on the BST/alumina substrate by a photolithographic lift-off technique. A modified lift-off technique using positive imaging photoresist Shipley 1813 was developed and used in this work. After the photoresist patterns were prepared, a two-layer metallization stack was deposited. Initially, a thin layer of Cr (20 nm ) was deposited. This acts as an adhesion layer. Subsequently, 0.5 $\mu$m of Cu was deposited by thermal evaporation without breaking vacuum in a dual deposition chamber. Finally a capping layer of Pt (0.03 $\mu$m ) was deposited on top of the Cu layer. This was done to prevent ambient oxidation of copper. To complete the IDC fabrication, metal lift-off was done in Microchem PG remover at 60 °C. The fingers of the BST interdigital varactor had a length of 195 $\mu$m and width of 10 $\mu$m . The finger spacing was 3 $\mu$m and the number of fingers was 16. The discrete BST varactors were subsequently diced and characterized, see Fig. 1. Capacitance and the loss tangent data after dicing is the same as that measured before the dicing process. A tunability of 1.5:1 or 33 % was recorded for 35 V bias (116 kV/cm). The loss tangent at zero bias was 0.015 and this decreased by a factor of three to 0.005 at 35 V bias. The high-frequency characterization technique reported in [7] was used. Formulae for calculating the capacitance of multi-layered thin-film interdigital capacitors can be found in [8]. We also measured the variation of capacitance and loss tangent over a wide temperature range from $-170$ °C to +230 °C. As shown in Figs. 2(a) and 2(b), the curves show a typical ferroelectric to paraelectric transition at around +3 °C. This is expected for a 60/40 composition of the BST target used for this work. Upon approach to T$_c$ (Curie temperature) during cooling, the loss tangent increases, heralding the onset of the ferroelectric phase.

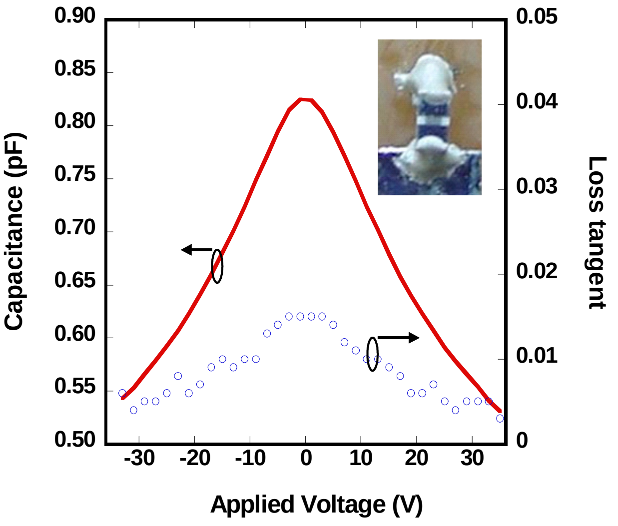
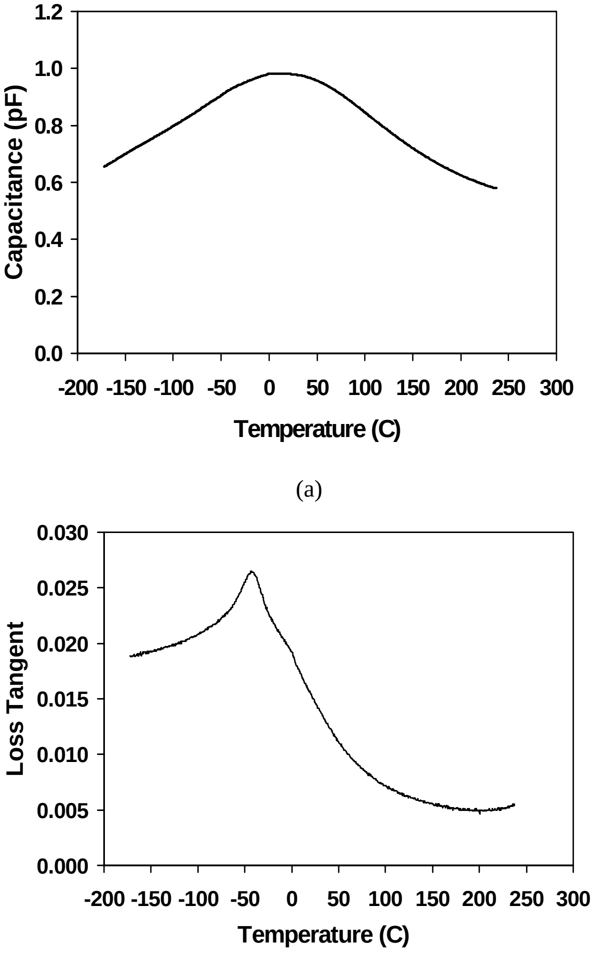


Fig.1. Representative tuning curve for discrete (0603) thin-film BST interdigital varactor on polycrystalline alumina at 1 MHz.



(a)

(b)

Fig.2. Temperature characterization. (a) Capacitance Vs. Temperature. (b) Loss Tangent Vs. Temperature.

## III. TUNABLE COMBLINE FILTER DESIGN AND CHARACTERIZATION

A 2nd-order filter was designed based on a lowpass lumped element prototype with inverters. From the lowpass prototype an initial estimate of the inter-resonator couplings was first determined. The filter was constructed on an FR4 board with a substrate thickness of 62 mil (1.57 mm), dielectric constant of 4.7 and loss tangent of 0.016. With the knowledge of the coupling coefficients the electrical prototype was then converted to a physical layout using ADS [9]. Upon simulation, the resulting values of the loading capacitors were found to be 0.7 pF each. The nominal electrical length of the resonators was 45 degrees at the center frequency of the filter. The discrete BST varactors were attached at the end of the resonators using conductive epoxy. The biasing circuitry consists of two discrete capacitors of high value (1 nF ) and rated to 200 V. This ensures an RF short while providing a node for DC tuning. High impedance tuning lines were then connected to a DC power supply. The assembled bandpass filter is shown in Fig. 3.

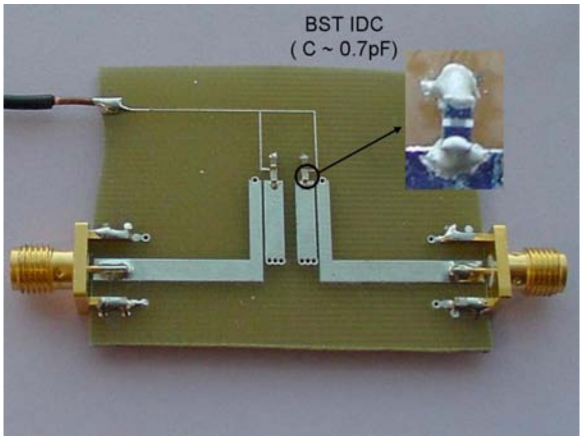


Fig.3. Assembled bandpass filter.

The filter was measured on a HP 8510C vector network analyzer and bias was varied from 0 to 130 V using a HP 4142B DC source. The tuning response of the filter is shown in Fig. 4. The zero bias insertion loss was 4.9 dB and the filter was centered at 2.14 GHz. At the high end of the tuning range, the center frequency moved to 2.61 GHz and the insertion loss improved to 2.9 dB. This is in part due to higher Q factor of the BST varactors with increasing bias and also due to better matching at lower capacitance values, see Fig. 5. The *Q* factor of the BST varactors was estimated using a comparison of the measured and modeled data and was found to be approximately 20 in the operating range. The return loss of the filter was better than 11 dB over the entire tuning range. A comparison of the measured and modeled data at zero-bias is shown in Fig. 6. The model holds equally well at other bias voltages. There is a slight deterioration in the upper passband due to the parasitics associated with the bias circuitry.

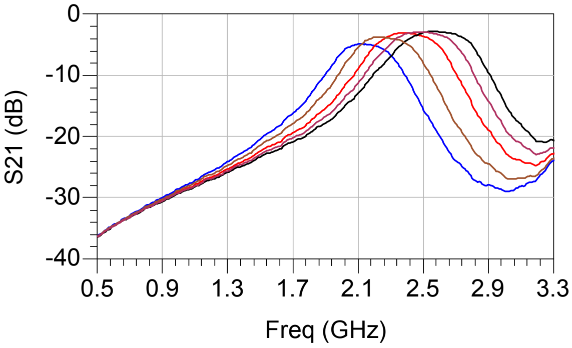


Fig. 4. Measured insertion loss of the filter with applied bias; 0 V, 30 V, 60 V, 90 V, and 130 V bias from left to right.

A summary of the filter tuning result can be found in Table I. The DC current was recorded at each bias point. The worst case total DC power consumption is about 0.7 $\mu$W . This compares very favorably with semiconductor varactor diodes where the power consumption is of the order of tens of microwatts.

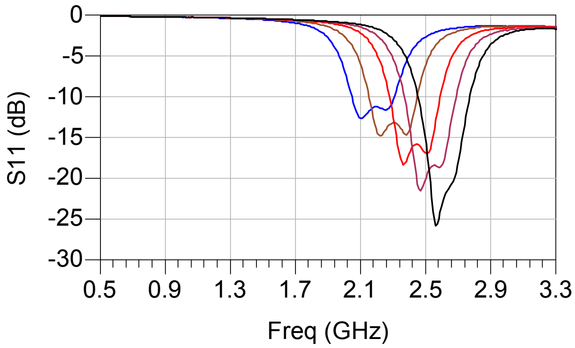


Fig. 5. Measured return loss of the filter with applied bias; 0 V, 30 V, 60 V, 90 V, and 130 V bias from left to right.

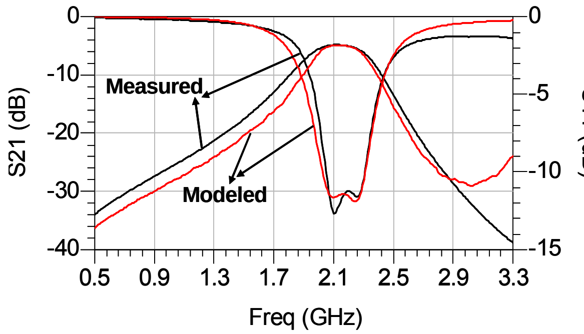


Fig. 6. Comparison of measured data and circuit model at 0 V.

TABLE I

SUMMARY OF FILTER RESULTS

| Bias Voltage (V) | Center Frequency (GHz) | Insertion Loss (dB) | Return Loss (dB) | DC Current (nA) |
|---|---|---|---|---|
| 0 | 2.14 | 4.93 | 11.2 | - |
| 20 | 2.22 | 4.23 | 12.3 | 1.5 |
| 40 | 2.32 | 3.56 | 14.1 | 3.4 |
| 60 | 2.40 | 3.10 | 15.1 | 3.7 |
| 80 | 2.48 | 3.01 | 17.6 | 5.1 |
| 100 | 2.53 | 2.89 | 19.3 | 5.4 |
| 120 | 2.58 | 2.89 | 20.0 | 5.6 |
| 130 | 2.61 | 2.92 | 21.8 | 4.5 |

## IV. NONLINEAR CHRACTERIZATION

As is evident from Fig. 1, the BST varactor is nonlinear. The nonlinear characterization was done at 0 V bias which represents the worst case operating condition. We present the nonlinear characterization of the filter using a two-tone test and also a digitally-modulated signal. The input power of the two tones was swept up to 8 dBm and the output power level of the tones and the intermodulation products was recorded. An IP3 of +32 dBm was found from extrapolation, see Fig. 7.

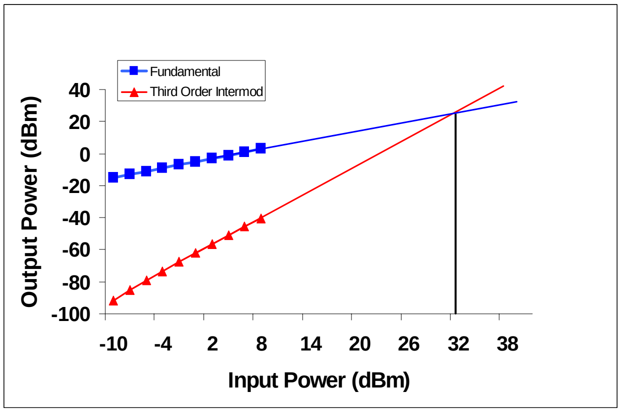


Fig. 7. Two-tone intermodulation measurement of the filter at 0 V.

The filter was also characterized using a CDMA 2000 pilot signal with power levels up to 26 dBm. The ACPR was measured in a 30 kHz bandwidth at an offset of 750 kHz from the center frequency of 2.14 GHz. The ACPR was found to be better than − 50 dBc, see Fig. 8. The ACPR results are consistent with the measured IP3 up to 18 dBm input power where higher order nonlinearity starts to cancel the third order component resulting in a distortion notch around 25 dBm input power. The 4:1 ACPR slope of the distortion characteristic after the notch is indicative of a fifth order nonlinearity; although, there is 3 dB of asymmetry implying that a baseband even order interaction term is present.

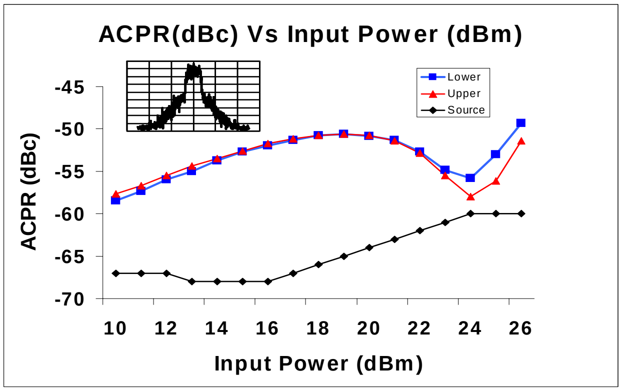


Fig. 8. Adjacent Chanel Power Ratio (ACPR) of the filter for a CDMA 2000 signal at 0 V.

## V. CONCLUSION

Discrete thin-film varactors in standard 0603 footprint have been designed, fabricated and characterized. Temperature characterization showed optimized performance at room temperature and acceptable performance over a range of temperatures from − 170 °C to +230 °C. As an application of the discrete BST varactor technology, a 2nd-order tunable combline bandpass filter on FR4 substrate was presented. The center frequency tuning was found to be 22% for an applied electric field of 433 kV/cm (130 V bias). Nonlinear characterization of the filter showed an IP3 of +32 dBm and an ACPR of better than − 50 dBc for input power up to 26 dBm. It is expected that the discrete BST thin-film interdigital varactor technology will prove to be a viable candidate for frequency agile devices in the range of 1–6 GHz where it is advantageous to have thick transmission lines and the parasitics associated with the discrete varactor assembly can be tolerated.

## ACKNOWLEDGEMENT

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