A Tunable Combline Bandpass Filter Using Barium Strontium Titanate Interdigital Varactors on an Alumina Substrate

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Abstract — **Barium Strontium Titanate (BST) has a field-dependent permittivity that enables it to be used as a dielectric in a voltage-tunable capacitor or varactor. A tunable combline bandpass filter was designed and characterized using BST varactors fabricated on a polycrystalline alumina substrate with copper metallization and is 14 mm x 14 mm in size. The center frequency of the filter varies from 1.6 to 2.0 GHz with the application of 200 V tuning voltage. A 25% tuning range was achieved using a tuning field strength of 300 kV/cm. The zero bias insertion loss was 6.6 dB and this decreased to 4.3 dB at the high bias state. The return loss was better than 10 dB.**

Index Terms — **Barium Strontium Titanate (BST), ferroelectric, microstrip filters, resonators, thin film devices, tunable filters, varactor.**

I. INTRODUCTION

Increased spectrum coverage with multifunctional RF electronics is driving the development of dynamically variable electronic components. With these components better channel selectivity and reduced size and weight are obtained since the same hardware can be used at multiple bands. Various tunable components such as ferroelectric-based varactors [1], micro-electro-mechanical systems (MEMS) [2], and semiconductor varactors have been investigated as enabling technologies for such tunable front ends. In this paper the focus is on using thin-film Barium Strontium Titanate (BST), a ferroelectric with a voltage dependent permittivity. It is a scalable low-cost material compatible with existing manufacturing processes and which also offers relative ease of integration and packaging. BST has received considerable attention as a tunable material for microwave devices. It can be fabricated using standard thin-film processes such as RF magnetron sputtering and metalorganic chemical vapor deposition (MOCVD). Considerable research has been done in the area of ferroelectric-based phase shifters, matching networks and tunable filters [3]–[5]. Most BST-based filters have been designed with discrete varactors [1], [4]. These realizations utilized parallel-plate varactors and yielded insertion loss in the range of 3–7 dB operating as low as 200 MHz and as high as 2 GHz. Another implementation was a thin-film distributed filter centered at 2.5 GHz with a 15% tuning range and was implemented using thin-film strontium titanate and HTS (high temperature superconductors) at 4 K [3]. BST-based tunable filters have been typically fabricated on single crystal substrates since high quality BST films can be epitaxially grown on such substrates at high temperatures. However, they are expensive and not widely used in the microwave industry. The objective of this work was to develop a low-cost tunable filter using a single-step fabrication process. We have developed a room temperature implementation of a voltage-tunable planar combline filter using thin-film BST interdigital varactor on polycrystalline alumina and inexpensive copper metallization. Alumina is commonly used in the microwave industry and is also low cost. These filters require tuning voltages in the range of 100–200 V compared to filters with parallel-plate designs which require tuning voltages in the range of 2–20 volts.

II. TUNABLE FILTER DESIGN

Tunable filters using BST thin-film varactors can be implemented in various topologies. There are essentially two choices for each topology: a lumped element circuit or a distributed implementation. A distributed approach was taken in the implementation of BST varactor based bandpass filter in LTCC technology [5]. This can be contrasted with the lumped element approach where the BST thin-film varactor is used in discrete form and wire bonded to other lumped components [1], or co-fabricated with inductors [4]. The latter implementation is usually limited by the low Q factor of the inductors available in integrated manufacturing process. However, it should be mentioned, that the lumped element approach offers a size advantage at the low microwave frequencies since the resonator length at such frequencies is of the order of a few centimeters. A distributed element approach was chosen for the work presented here since it allows the integration of the BST varactor in the circuit in the same fabrication step; this improves the Q factor by minimizing the series resistance [6]. A 3 rd-order combline bandpass filter was designed with a center frequency of 1.75 GHz and a 3 dB passband equal to 20% of the center frequency. The filter was designed using the MFilter synthesis tool in the GENESYS Suite from Eagleware [8]. The initial design was then tweaked and optimized for manufacturability. The capacitive loadings at the end of the resonators were changed to be equal since a tolerance of the order of a few tens of femtofarads is difficult to achieve. Furthermore, all widths and spacings were made equal and this resulted in a physically symmetrical filter. The nominal electrical length of the resonator was 57^o at the center frequency and the impedance was 52.2 Ω. A tapped design was used for the input and output feed and the impedance of the feed lines was 50 Ω. The schematic of the optimized filter is shown in Fig. 1, the nominal BST loading capacitor was found be 1.26 pF for the desired response. The fingers of the BST interdigital varactor had a length of 200 μm and width of 5 μm. The spacing of the fingers was 5 μm and there were 24 fingers. Formulae for calculating the capacitance of multi-layered thin-film interdigital capacitors can be found in [7].

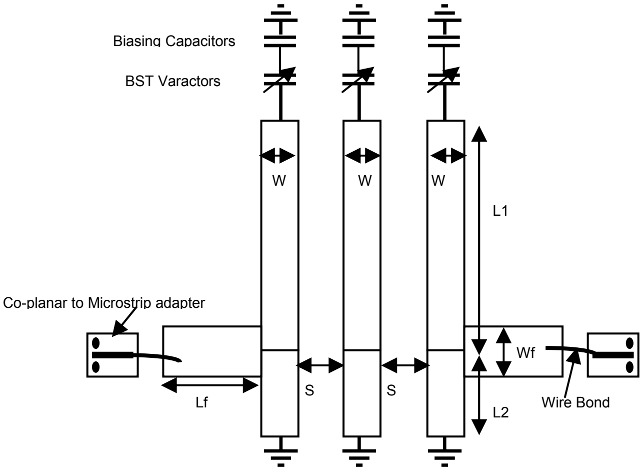

Fig.1. Schematic of the bandpass filter

The filter parameters were found to be as follows: W = 550 μm, S = 450 μm, L_1 = 5900 μm, L_2 = 4600 μm, W_f = 600 μm, L_f = 5225 μm. At the end of each BST varactor a 1 nF DC blocking capacitor with a rating of 200 V was attached. This served as the bias point for the BST varactors while providing a RF ground path for the high frequency signal. Parasitic resistances and inductances were also modeled in the design phase and filter parameters were adjusted to achieve the desired filter response. The layout of the filter was done in ADS (Advanced Design System).

III. IMPLEMENTATION

In this work we have chosen polycrystalline alumina (Al_2O_3) as the substrate for fabrication of the BST varactors and tunable filters. Alumina is an excellent substrate for frequency-agile devices since it exhibits low loss tangent (~10^{-4}) in the microwave range. It is also low cost when compared to single crystal substrates conventionally used such as MgO, $LaAlO_3$, and Al_2O_3 (sapphire). Furthermore, the coefficient of thermal expansion of alumina (~9 ppm) is closely matched to BST and hence high temperature processing is possible without cracking the BST thin films. A representative tuning curve of the BST thin-film interdigital varactor on alumina is shown in Fig. 2. A 1.7:1 (40%) tuning ratio is achieved for a varactor with 3 μm finger spacing and 35 V bias. This corresponds to a 120 kV/cm tuning field and is one of best results to date for BST varactors on any substrate.

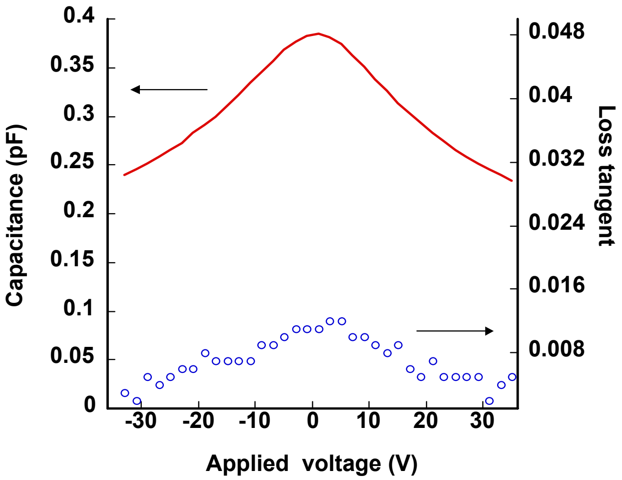

Fig.2. Representative tuning curve for thin film BST interdigital varactor on polycrystalline alumina at 1 MHz

Radio frequency magnetron sputtering was used to deposit 600 nm thick ($Ba_{0.75}Sr_{0.25}$)TiO_3 thin films on 14mm x 14 mm and 635 μm thick, one side polished alumina substrate. The deposition temperature was maintained at 300°C. A sputtering gas mixture of oxygen and argon and 10 mtorr total pressure was used for depositing the BST thin films. After deposition the films were annealed in air to obtain fully crystalline films. The details of the modeling and characterization of BST thin-film interdigital varactors on alumina has been published elsewhere [6]. A standard photolithography and metal lift-off technique was used for defining the filter pattern on the BST/ alumina substrate. A bilayer technique using multiple layers of lift-off resist and positive imaging photoresist was used to make a thick photoresist stack on the samples. After exposure and development of the photoresist, the sample was metallized. A thin layer of Cr (0.02 μm) was deposited first by magnetron sputtering followed by 1 μm of Cu deposited by thermal evaporation. Cu was chosen as the top electrode metal in this work since it provides the highest conductivity of any base metal and it is inexpensive compared to noble metal electrodes (e.g. Au and Pt) which have been used in most oxide-based microwave devices to date. Finally a capping layer of Pt (0.03 μm) was deposited on top of the Cu layer. This was done to prevent ambient oxidation of copper. Metal lift-off was then performed to define the complete filter structure. The backside of the alumina substrate was metallized using Cr (0.02 μm) and Cu (1 μm), this acts as the ground plane. After fabrication the filter was attached using conductive epoxy to a high-frequency laminate, see Fig. 3.

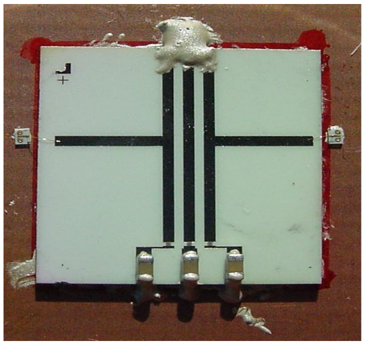

Fig. 3. Assembled bandpass filter

The copper surface of the board serves as the common ground plane. Since we did not use a “via” process the ground connections at the end of the resonators was made by “ground-wrapping” using conductive epoxy. The additional resistance (approximately 0.7–1 Ω for each ground connection made) introduced by this technique of grounding has been included in the simulation. The input and output connections to the filter was made using J-Micro CPW-to-Microstrip adaptors [9] and wire bonds.

IV. MEASURED RESULTS AND DISCUSSION

The filter was measured (see Fig. 4) by a HP 8510C Network Analyzer using a 150 μm pitch GSG (ground-signal-ground) probe from GGB Industries [10]. An LRM calibration was performed using the CS–5 calibration substrate from GGB Industries.

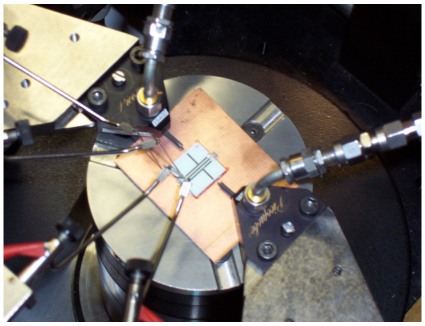

Fig.4. Filter under test

The zero bias response can be seen in Fig. 5 and the filter is centered at 1.6 GHz with an insertion loss of 6.6 dB. This downward shift in the center frequency can be explained by a slight increase in the resonator length due to the use of epoxy for “ground–wrapping”. The overall mask dimensions of the filter were 13mm x 13mm. The filter was fabricated on a 14mm x 14 mm substrate and this leads to an extension of the line length by approximately 1000 μm. This explains the downward shift in the center frequency compared to a designed value of 1.75 GHz. The BST varactors at the end of the resonators were measured to be 1.16 pF at 1 MHz. A comparison of the measured and simulated zero bias filter response including these effects is shown in Fig. 5 and the agreement is quite good.

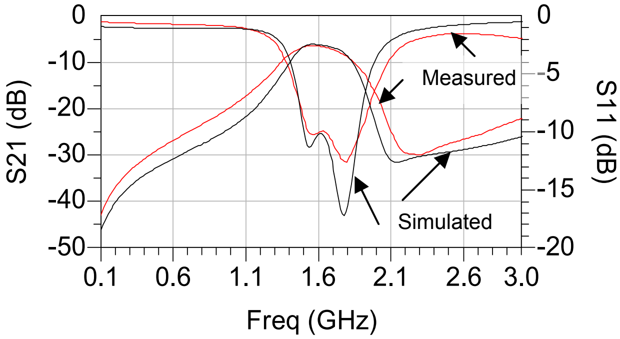

Fig. 5. Comparison of the measured and simulated filter at zero bias

The BST varactors had a zero bias Q factor of about 20 in the range of 1–2 GHz. The varactors were biased using DC probes at one end of the DC blocking capacitors. All varactors were tuned in tandem. The DC bias was varied from 0 V to 200 V in steps of 25 V and the S-parameter data was recorded at each bias point. The BST varactor tuning was found be to be 2:1 (50%) for 200 V bias. The center frequency of the filter tuned from 1.6 GHz at zero bias to 2 GHz at 200 V bias, see Fig. 6. The frequency tuning achieved was 25% and the filter is capable of covering the GPS and the GSM bands at 1800 and 1900 MHz. In an improved fabrication process where the parasitics are eliminated, the tuning range of the filter would be further increased. The mid-band insertion loss was 6.6 dB at zero bias and this decreased to 4.3 dB at 200 V bias. The decrease in insertion loss with increasing bias is in part due to the increased Q factor of the BST varactors with bias (see Fig. 2) and also in part due to improved matching that results with change in capacitance (see Fig. 7). A summary of the filter tuning results can be found in Table I.

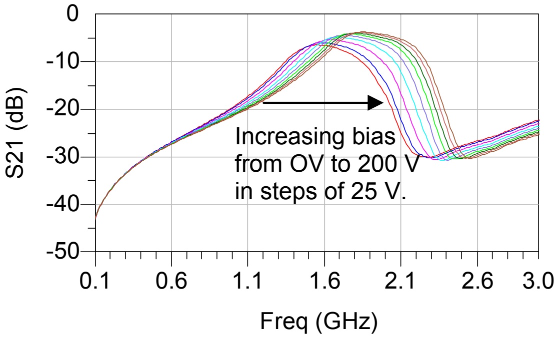

Fig. 6. Measured insertion loss of the filter with applied bias

The tuning was achieved by an electric field of 300 kV/cm. The BST interdigital varactors were designed with a finger width and spacing of 5 μm but a slight overdevelopment of the liftoff resist lead to an increase in the finger spacing by 1.5–2.0 μm. It should be noted that the tuning voltage can be reduced by decreasing the finger spacing and simulation results show that with 3 μm spacing, similar tuning can be achieved by voltages less than 100 V.

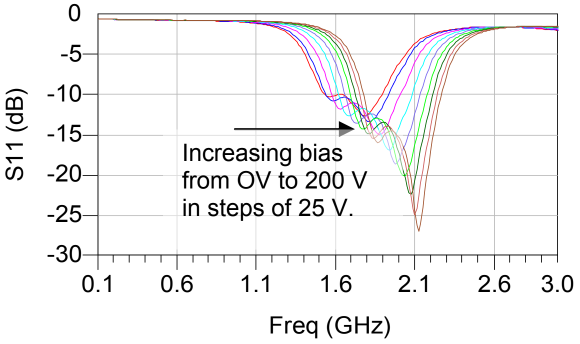

Fig. 7. Measured return loss of the filter with applied bias

TABLE I
SUMMARY OF FILTER RESULTS

Bias Voltage (V)	Center Frequency (GHz)	Insertion Loss (dB)	Return Loss (dB)
0	1.60	6.55	10.00
25	1.64	6.13	10.30
50	1.74	5.80	11.00
75	1.80	5.33	12.00
100	1.84	4.90	12.35
125	1.89	4.70	12.94
150	1.92	4.45	13.40
175	1.95	4.37	13.90
200	2.00	4.30	14.70

Though tuning voltages are rather high compared to parallel plate BST varactors, a major advantage is the simple and inexpensive fabrication process. It should also be noted that such high voltages can be readily achieved in non-portable devices using DC to DC converters at low cost. In comparison with commercially available fixed frequency bandpass filters at similar frequencies the BST filters have a additional loss of about 2.5–3.5 dB. However, this situation can be straightforwardly remedied by using a “via” process and a thicker metallization. The “via” process would reduce the parasitic resistance at the end of the resonator and simulation results show that it would reduce the insertion loss by approximately 1–1.5 dB. The effective metal thickness used in our process was about 0.8 μm (physical thickness was 1 μm) since the conductivity of evaporated copper was approximately 80% of the base metal. The skin depth of copper is 1.65 μm at 1.6 GHz and hence the insertion loss can be considerably reduced by increasing the metal thickness. Furthermore, the wire bond and the CPW-to-Microstrip adapters at the input and output introduce an additional 0.5–0.7 dB of loss. In an integrated process they would be eliminated leading to further improvement in insertion loss.

V. CONCLUSION

A tunable combline filter based on thin-film BST interdigital varactors and with a center frequency of 1.6 GHz was demonstrated. The filter was fabricated on a standard polycrystalline alumina substrate using copper metallization. The measured filter results closely matched the simulation results when all parasitic elements were accounted for. The zero-bias insertion loss of the filter was 6.6 dB and this decreased to 4.3 dB at 200 V bias. The tuning was found to be 25% for an applied electric field of 300 kV/cm. It is expected that the BST thin-film interdigital varactor on polycrystalline alumina and copper metallization will be a competitive technology and a cost-effective solution for the next generation of multi-band and multi-standard devices.

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