An Electronically Tunable Microstrip Bandpass Filter Using Thin-Film Barium–Strontium–Titanate (BST) Varactors

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***Abstract*—A tunable third-order combline bandpass filter using thin-film barium–strontium–titanate varactors and fabricated on a sapphire substrate is reported. Application of 0–200-V bias varied the center frequency of the filter from 2.44 to 2.88 GHz (16% tuning) while achieving a 1-dB bandwidth of 400 MHz. The insertion loss varied from 5.1 dB at zero bias to 3.3 dB at full bias, while the return loss exceeded 13 dB over the range. The third-order intercept of the filter was found to be 41 dBm.**

***Index Terms*—Barium strontium titanate (BST), combline filter, ferroelectric films, intermodulation distortion, microstrip filters, resonators, thin-film devices, tunable filters, varactor.**

I. INTRODUCTION

TUNABLE filters have been investigated for insertion in multifunctional multiband RF and microwave systems. Compared to a bank of fixed filters, a tunable filter promises greater functionality, better channel selectivity, reduced size, and lower weight since the same hardware can be employed at multiple bands. Many technologies have been considered. Mechanically tunable filter technology is well established, but such filters are slow and bulky [1]–[4]. More recently, miniature incarnations of mechanically tunable filters have been implemented using micro electromechanical systems (MEMS) varactors [5]. MEMS-based filters [6], [7] are small and have low insertion loss, but the fastest tuning speeds are around a microsecond. The reversed-biased semiconductor diode is another varactor technology enabling tunable-filters, but these have relatively high insertion loss (because of low Q) at microwave frequencies and have limited power-handling ability [8], [9].

Thin-film ferroelectrics, such as barium strontium titanate (BST) have been investigated for application in low-loss filters that can be tuned quickly [10]–[14]. Used in the paraelectric phase, these materials typically exhibit a large dielectric constant ($\varepsilon_r = 300$–800 for BST) that can be changed by an external bias voltage. Since the paraelectric phase is characterized by the absence of domain walls, relatively low loss is achieved compared to the material in the ferroelectric phase. Ferroelectrics can be fabricated on a variety of substrates using standard semiconductor manufacturing processes. They can be tuned at nanosecond speeds, and have relaxed packaging requirements compared to MEMS. A large design space enables tradeoff of power-handling capability with the bias voltages required to achieve tuning [15]. Loss in BST filters derives from dielectric loss and conductor loss.

BST varactors can be fabricated either in a parallel plate [i.e., metal–insulator–metal (MIM)] or interdigitated capacitor (IDC) configurations. Being 1 μm or less thick typically, MIM varactors require much lower tuning voltages (5–20 V for maximum tuning) compared to IDC varactors with 3 μm or more finger spacing (100–200 V). However, with MIMs, 1 μm or less lithography is needed to realize the 0.1–3 pF capacitances typically required in lumped and distributed-lumped microwave filters. With thin-film BST-based IDCs, the required capacitor values can be obtained with a gap spacing of 3 μm or so. Fortuitously, an IDC also enables designs that require only a single level of metallization.

Tunable thin-film BST-based filters typically have achieved insertion losses in the range of 3–7 dB with a center frequency of 0.2–1.4 GHz [16]–[18]. These filters used discrete MIM BST varactors and there have been reports of tunable filters using BST thin-film IDC varactors above 1 GHz. A bulk BST-based tunable filter implemented in low-temperature co-fired ceramic (LTCC) with 4.3 dB of insertion loss and a center frequency in the range of 1710–1980 MHz was reported in [19]. In this paper, we present a room-temperature third-order combline bandpass filter using thin-film BST IDC varactors. Single-layer lithography on sapphire and copper metallization is used to achieve insertion losses in the 3–5-dB range at 2.5 GHz. Fabrication and design details, measurement results, and nonlinear characterization of the filters are presented.

II. FABRICATION OF BST INTERDIGITATED VARACTORS

In this study, we use single crystalline sapphire as a substrate for deposition of BST thin film by RF sputtering. Sapphire has attractive microwave properties such as low-loss tangent ($\tan\delta = 0.0001$) at microwave frequencies and high dielectric strength. The coefficient of thermal expansion (CTE) (CTE $\sim$

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9.0 ppm) of sapphire is close to that of BST (CTE $\sim$ 8 ppm) and, hence, high-temperature annealing is possible without cracking the BST thin films.

An RF magnetron sputtering technique was used to deposit ($Ba_{0.75}Sr_{0.25}$) TiO_3 on polished single crystalline c-plane sapphire substrates (Commercial Crystal Laboratories Inc., Naples, FL). A Ba/Sr composition of 75/25 was chosen for optimum balance between dielectric tunability and loss tangent. The substrates were 10 mm $\times$ 10 mm in size and 500-μm thick. Sputtering was done in an argon/oxygen mixture at a pressure of 10 mtorr and a temperature of 300 °C to obtain a 0.6-μm-thick BST film. After deposition, the film was annealed at 900 °C for 20 h to obtain a fully dense and crystalline BST thin film. A hysteresis test was performed to confirm that the thin film was in the paraelectric phase. The crystalline structure of the film was investigated using a diffractometer with a CuK_α radiation source and showed a fully crystalline BST perovskite structure.

Noble metals such as platinum, gold and iridium have typically been used as electrodes in oxide-based (e.g., BST) thin-film devices, as they are generally nonreactive upon contact with oxides. As well, their large work functions result in Schottky contacts. However, platinum and iridium have high resistivity and, thus, high electrode thicknesses (several micrometers) are necessary to achieve acceptably low equivalent series resistance (ESR) of a device. This leads to difficulty in fabricating IDCs with finger spacing of a few micrometers. Gold is to be avoided because it is expensive. We have developed inexpensive low-resistivity chrome/copper electrodes for BST devices providing good adhesion of the electrodes to the BST and minimizing the deleterious oxidation effect at the metal/BST interface [20]. A thin layer of chromium (0.03 μm) was sputtered followed by deposition of 1.0 μm of copper by thermal evaporation. The final step was depositing a thin 0.03-μm capping layer of platinum to prevent ambient oxidation of copper and also to facilitate adhesion of gold wire bonds to the feed lines. A step-by-step process flow is shown in Fig. 1 yielding an IDC of the form shown in Fig. 1(g).

Standard photolithography and a metal liftoff process were used to define the fingers of the interdigitated varactor and feed electrodes. A liftoff process was used since it utilizes benign chemicals, which do not harm the BST. A consequence of using liftoff is that electrode thickness is limited. Positive imaging photoresist Shipley 1813 and Microchem LOR 5A was used to deposit a thick bilayer photoresist stack for liftoff. After standard UV exposure and development of the photoresist, the sample was metallized. Finally, liftoff was done in a Microchem Remover PG solution to define the interdigitated fingers.

III. Filter Design and Fabrication

The BST IDCs were used to realize third-order tunable combline bandpass filters. Initial filter synthesis was undertaken using the MFilter tool in GENESYS[1] and, subsequently, dimensions were optimized to achieve the filter specifications and also to equalize both the BST capacitor values and the sensitivity of the filter to BST capacitor variations (under bias).

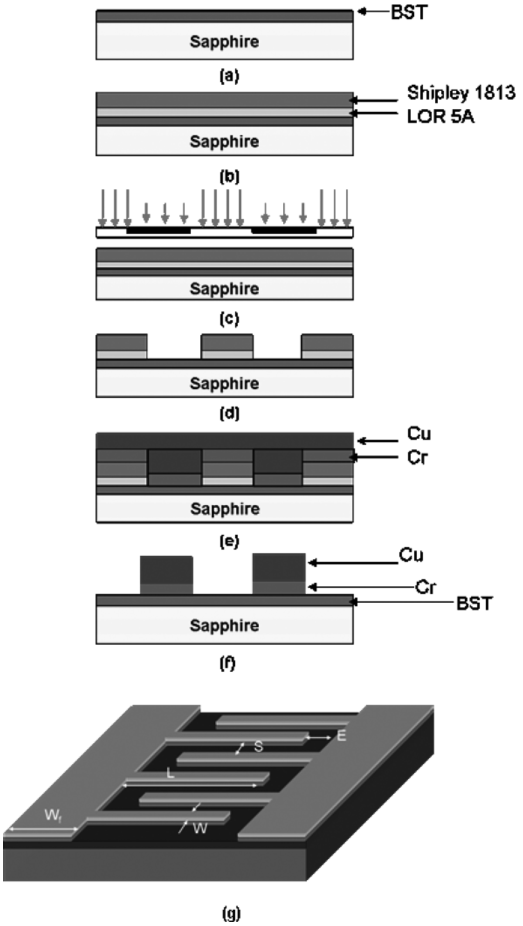

Fig. 1. Process flow for BST interdigitated varactor fabrication. (a) Deposition of BST thin film by sputtering. (b) Positive imaging resist and liftoff resist deposition. (c) UV exposure. (d) Resist development. (e) Cr and Cu deposition. (f) Patterning of top-metal by liftoff. (g) Schematic of interdigital capacitor.

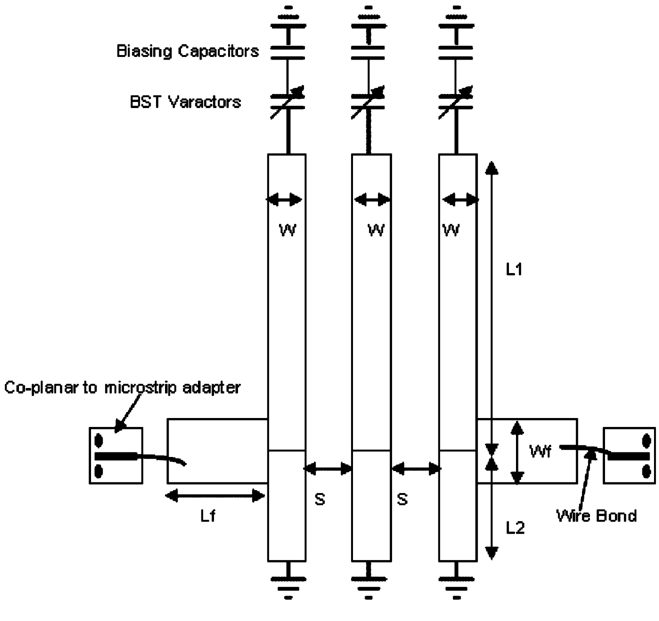

Fig. 2. Schematic of the tunable combline bandpass filter.

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[1] Eagleware Corporation, Norcross, GA. [Online]. Available: http://www.eagleware.com

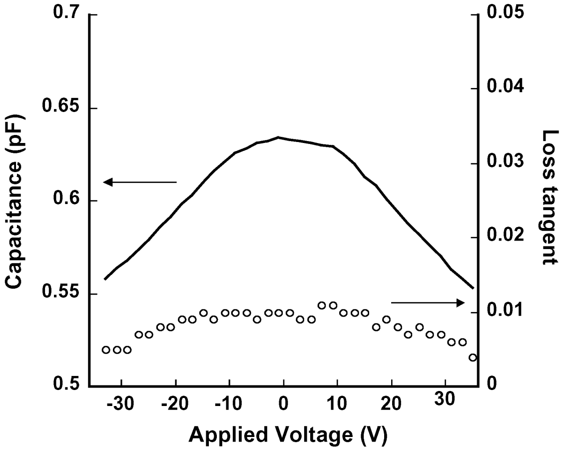

Fig. 3. Nominal tuning curve of the BST IDC varactor (20 fingers each of width 5 μm and length 100 μm, finger spacing is 5 μm) at 1 MHz.

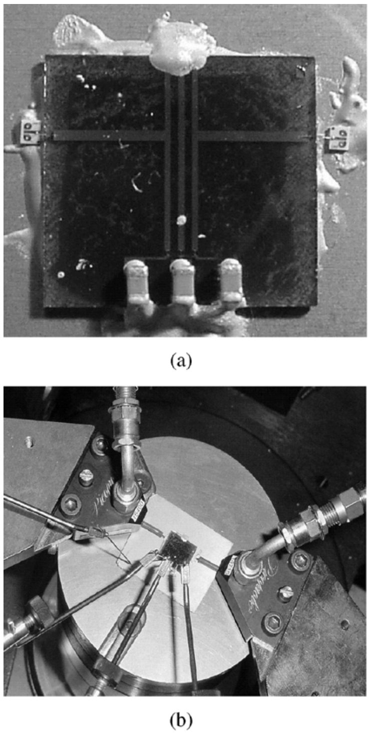

Fig. 4. Assembled filter. (a) Wraparound ground and microstrip-to-CPW adaptors. (b) Filter under test.

This procedure ensured a smooth variation of the center frequency f_M of the filter under bias and minimized distortion of the filter bandpass characteristics during tuning. Filter dimensions were also adjusted to permit ground wrapping for the top and bottom grounds, as shown in Fig. 2. The optimized filter parameters were $W = 235$ μm, $S = 235$ μm, $L_1 = 4500$ μm, $L_2 = 3000$ μm, $W_f = 430$ μm, and $L_f = 4377.5$ μm, yielding a filter with a midcenter frequency f_{M0} of 2.4 GHz and a 1-dB bandwidth of 300 MHz. The nominal electrical length of the resonators was 58° at the center frequency with a characteristic impedance of 69 Ω.The required capacitance of the BST varactors was 0.6 pF, achieved using a 12-finger IDC of length 200 μm, width 5 μm, and spacing (5 μm) (after [21] and [22]).

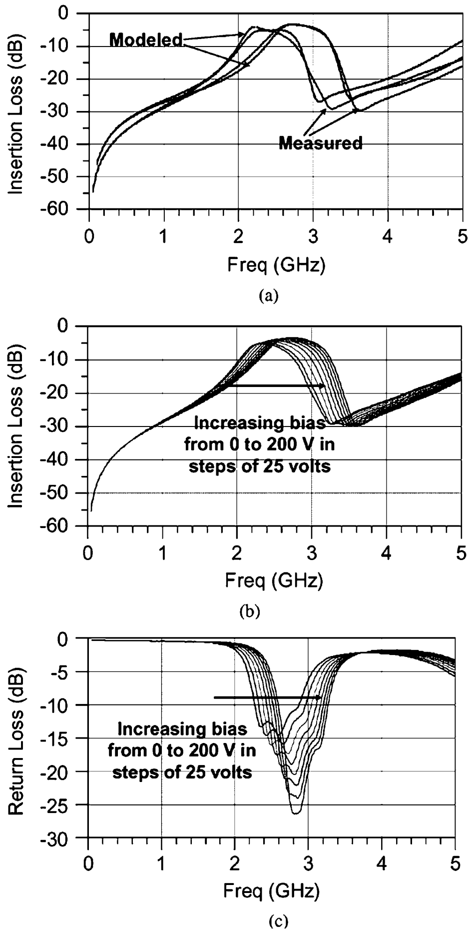

Fig. 5. Measured filter data. (a) Comparison of model versus measured data for 0- and 200-V bias. (b) Insertion loss versus bias. (c) Return loss versus bias.

The characteristic of one IDC is shown in Fig. 3. The varactor shows a 12% tuning with an applied bias of 35 V at 1 MHz. The finger spacing was 5 μm and, hence, there was a tuning field of 70 kV/cm across adjacent fingers. The Q factor of the varactor was found to be 100 at 0-V bias, increasing to 250 at 35-V bias, both measured at 1 MHz.

The assembled bandpass filter and the filter under test is shown in Fig. 4(a) and (b), respectively. The biasing network for each BST IDC consisted of a 1.0-nF dc blocking capacitor rated at 200 V in series with the IDC. In final assembly, the ground connections were made using conductive epoxy and wrapping it over the edge of the substrate. CPW-to-microstrip adaptors[2] at the feed lines enabled CPW probing.

IV. FILTER CHARACTERIZATION

The measured filter characteristics are shown in Fig. 5. The bias was varied up to 200 V and the S-parameters recorded at each bias point. A filter model was implemented in Agilent ADS using measured parasitic data and other lumped-element parameters from the datasheets. The agreement between the modeled and measured insertion loss is shown in Fig. 5(a). For the sake of clarity, the comparison is shown only for two ends of the bias

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[2] J Micro Technology Inc., Portland, OR. [Online]. Available: http://www.jmicrotechnology.com

TABLE I
LEAKAGE CURRENT VERSUS BIAS VOLTAGE

Bias (V)	Current (nA)
25	22.68
75	48.87
125	66.20
175	67.54

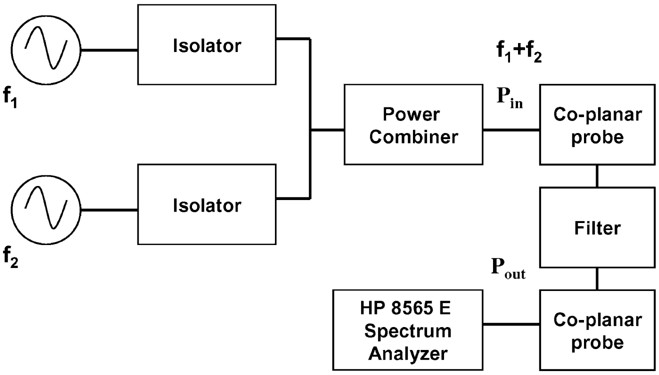

Fig. 6. Experimental setup for intermodulation measurements using tones at 2.35 and 2.36 GHz.

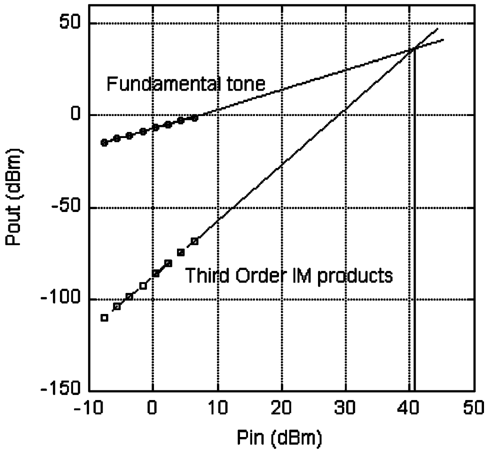

Fig. 7. Measured fundamental and intermodulation responses of the filter in a two-tone test.

range, but the model hold equally well at all bias voltages. The insertion and return losses of the filter are presented in Fig. 5(b) and (c), respectively, at bias points from 0 to 200 V in 25-V steps. The filter has a minimum zero bias insertion loss of 5.1 dB at 2.44 GHz. The filter was tuned to 2.88 GHz (16% tuning) with 200-V bias and the minimum insertion loss was further reduced to 3.3 dB. This was due in part to improved matching and also due in part to a higher Q factor of the BST varactors at high bias voltages. The return loss was better than -13 dB for all bias voltages. It should be noted that the measured 1-dB bandwidth of the filter was 400 MHz compared to the designed value of 300 MHz. Broadening was presumably due to parasitics that were not accounted for. This difference can be attributed to losses in the metal and also the parasitic associated with the filter assembly. Experiments with different metallization thickness indicate that insertion loss is dominated by electrode losses and not by losses in the BST. As previously reported in [23], a similar bandpass filter with 0.5 μm of sputtered copper showed an insertion loss of 8.3 dB at zero bias and 6.7 dB at 180-V bias. The total dc power consumer by the filter was approximately 12 μW over the range of bias voltage investigated. The total leakage current drawn by all three BST capacitors for four different bias voltages is listed in Table I.

The linearity of the tunable filter was characterized using a conventional two-tone intermodulation test (see Fig. 6) while ensuring that passive intermodulation of the test set was negligible. Results of the two-tone test are shown in Fig. 7 with a third-order intercept point (IP3) of +41 dBm. For comparison, the peak-to-peak voltage of a 1-W sinusoidal signal in a 50-Ω system is 20 V. It is worth noting that the relatively higher tuning voltages required for IDCs compared to MIM varactors renders them insensitive to a large swing in RF voltages and, therefore, leads to improved linearity, thus affording a much higher IP3.

V. CONCLUSION

A room-temperature tunable combline bandpass filter using a BST thin-film interdigitated varactor and a new metallization scheme has been presented. The bandpass filter achieved 16% tunability upon the application of 0–200-V bias. The 200-V bias required is not prohibitive, as negligible power is required to tune the IDC. The insertion loss of the filter was 5.1 dB at zero bias and decreased to 3.3 dB at a high bias state. An intermodulation test of the filter showed an IP3 of +41 dBm. With the current state of technology, a liftoff process was required to realize the IDCs, and this limits the top electrode thickness. This can be expected to change in the near future as etching technology improves by identifying electrode etchants that do not damage the BST film.

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