Voltage-Controlled RF Filters Employing Thin-Film Barium–Strontium–Titanate Tunable Capacitors

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***Abstract*—Tunable lowpass and bandpass lumped-element filters employing barium–strontium–titanate (BST)-based capacitors are presented. A new metallization technique is used, which improves the quality factor of the tunable BST capacitors by a factor of two. The lowpass filter has an insertion loss of 2 dB and a tunability of 40% (120–170 MHz) with the application of 0–9-V dc bias. The bandpass filter (BPF) has an insertion loss of 3 dB and a tunability of 57% (176–276 MHz) with the application of 0–6 V dc. The third-order intercept point of the BPF was measured to be 19 dBm with the application of two tones around 170 MHz.**

***Index Terms*—Barium–strontium–titanate (BST), ferroelectric, intermodulation distortion, metalorganic chemical vapor deposition (MOCVD), multilayer ground plane, paraelectric, tunable bandpass filter (BPF), tunable lowpass filter (LPF).**

I. Introduction

TUNABLE RF and microwave filters have wide applications in many types of communication systems such as receiver preselection, IF, and transmit filtering. Most of today's tunable filters rely on either mechanical or electronic tuning using varactor diodes or switched capacitors. Mechanically tunable filters have high power-handling capability with a low insertion loss. The main disadvantages of these filters are low tuning speed, large size, and mass [1]. Varactor-diode-based tunable filters are much faster, but they suffer from poor power handling and high losses at RF and microwave frequencies due to the low quality factor of varactor diodes at these frequencies [1], [2]. Switched-capacitor filter banks are more common, but they do not have a continuous tuning range and are not usually small. Recently, new technologies such as microelectromechanical systems (MEMS) [3], [4] and ferroelectric thin films [9]–[13] have been exploited for the development of low-loss and miniature tunable filters. MEMS-based tunable filters employ either MEMS switches or MEMS varactors. A good example of a MEMS-based tunable bandpass filter (BPF) at VHF has been presented in [5] with an insertion loss of approximately 4 dB. With the advances in MEMS technology, lower insertion loss filters are expected. However, MEMS have stringent packaging requirements and complicated biasing schemes [6]. Most of the current research activities concentrate on improving the power-handling capability and reliability of the MEMS-based structures [7], [8].

Ferroelectric materials have been extensively studied for nonvolatile memory applications and dynamic random access memory (DRAM) [14]. They have a characteristic temperature—the Curie temperature T_C—at which the material makes a structural phase change from a polar phase (ferroelectric) to a nonpolar phase (paraelectric). The ferroelectric phase possesses an equilibrium spontaneous polarization that can be reoriented by an applied electric field (i.e., hysteresis loop). At the paraelectric phase, the spontaneous polarization equals zero, however, the relative dielectric constant (ε_r) remains large and can be changed with the applied electric field. This enables the fabrication of electronically tunable capacitors with typical tunabilities greater than 50% at dc-bias levels as low as 2–5 V [13], [16]–[20]. These capacitors can be used to construct tunable microwave devices, such as filters, phase shifters, matching networks, and voltage-controlled oscillators (VCO). 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 [9]–[13]. STO presents high tunability at significantly low temperatures (~77 K), thus allowing the incorporation of high-temperature superconductors (HTSs) for improved loss performance. Planar microstrip HTS tunable filters have been demonstrated for low-loss receiver front-end systems [11], [12], [21]. However, these filters can be very expensive and require tuning voltages of several hundred volts. Furthermore, since STO thin films exhibit very little tunability at room temperature (STO is an incipient ferroelectric with an extrapolated Curie temperature below absolute zero), they are not suitable for integration in systems operating at room temperature. Tunable filters based on BST thin films can overcome these difficulties. Depending on the specific composition, BST can be made tunable at room temperature. Other advantages of BST-based capacitors include the ease of integration with active devices such as monolithic microwave integrated circuits (MMICs), low-cost simultaneous fabrication of multiple parts, and low losses in

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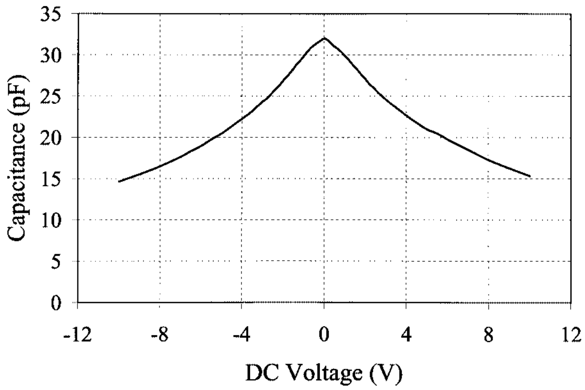


Fig. 1. C–V curve for a typical BST capacitor measured at VHF.

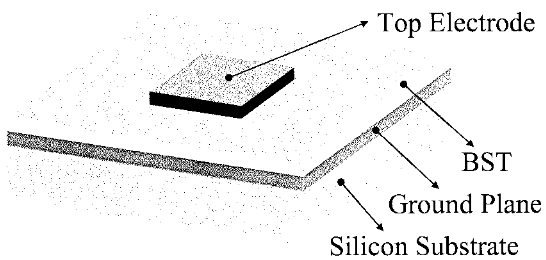


Fig. 2. Schematic illustration of the parallel-plate BST capacitors.

high-quality films and high power-handling capability [15]. In addition, due to the high dielectric constant of BST thin films (typically around 300) [22], capacitors with very small footprints can be fabricated on appropriately buffered substrates. The capacitance variation with the applied dc voltage for a BST capacitor used in this study is shown in Fig. 1. In this paper, a new metallization technique to improve the quality factor of BST capacitors is introduced and the design, fabrication, and measurement results for tunable lumped-element lowpass filters (LPFs) and BPFs based on BST capacitors are presented.

II. Fabrication of the BST Capacitors

The parallel-plate BST capacitors were fabricated on 500-μm-thick silicon wafers covered with approximately 500 Å of thermal SiO_2 and 5000 Å of Pt (this Pt layer acts as the device ground plane—see Fig. 2). Metalorganic chemical vapor deposition (MOCVD) technique was used to grow 3000-Å —thick $(Ba_{0.7}Sr_{0.3})TiO_3$ 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 [23], [24]. In this study, all BST films were uniformly deposited on 150-mm wafers, thus indicating the suitability for commercial mass production. Either sputtering or electron-beam evaporation techniques were used to deposit the 3000-Å—thick top electrodes completing the parallel —plate capacitor structures. Using standard photolithographic methods and reactive ion etching, the top platinum surface was patterned. Fig. 2 shows the schematic illustration of the parallel-plate BST capacitors fabricated. These capacitors were used to construct a BPF with an insertion loss of 7 dB [9]. To reduce this insertion loss, higher quality-factor BST capacitors were needed. The main source of the total loss for the BST capacitors is the conductor loss. It is certainly possible to reduce the conductor loss by increasing the electrodes' thickness and reducing the total resistance. To improve the quality factor of the BST capacitors, efforts were directed to improving the ground-plane metallization [25]. However, there are some challenges associated with this approach.

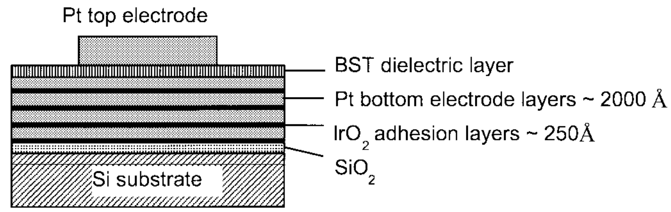


Fig. 3. Description of the multilayer ground-plane BST capacitor.

The bottom electrode must survive the BST deposition process remaining smooth, flat, and adherent to the substrate. Typically, BST is deposited between 650 °C–700 °C in an atmosphere composed of chemical precursors, which can be particularly aggressive. This environment, especially the high temperatures, can facilitate bottom-electrode degradation. Specifically, the thermal expansion mismatch between the silicon wafer and Pt electrodes results in appreciable residual strains upon cool down to room temperature. The potential outcome of large residual stresses includes bottom-electrode peeling and hillocking. These conditions are worsened by increasing the metal thickness; as the thickness is increased, the amount of residual stress increases as well. Thus, increasing the thickness to reduce the total resistance can result in mechanically unstable bottom-electrode layers, which are obviously undesirable for high-quality devices.

To avoid these problems, the adhesion between the platinum electrodes and the SiO_2 substrate surfaces must be improved—this can be difficult to accomplish. The authors have approached this problem by developing hybrid composite electrodes fabricated from interleaved layers of Pt and IrO_2 [26]. IrO_2 is a metallic oxide, which can promote Pt adhesion and mechanical stability. The composite electrodes consisted of alternating layers of 250-Å IrO_2 and 2000-Å Pt, as shown in Fig. 3. This stacking was continued until a total thickness of 1.3 μm was reached. This metallic stack was able to survive the BST deposition process without mechanically failing, and the resistance was reduced as expected by the thickness increase. High-frequency measurements were performed on the BST deposited on these thick electrodes to determine if the quality was similar to samples deposited on the traditionally thin Pt layers. The loss tangent of the BST material on these thick layers was measured to be 0.008 between 45–500 MHz, which is similar to the values obtained from thin platinum bottom-electrode BST capacitors [16], [26]. The total quality factor (device Q) of a 65-pF BST capacitor having multilayer ground plane was measured to be 63 at 45 MHz, a factor of two improvement compared to previously fabricated BST capacitors with thin bottom electrodes. In comparison, the Q factors of commercially available varactor diodes with similar capacitance ($\sim$65 pF) are in the range of 30–150 at 45 MHz. With the advances in BST film deposition and processing,

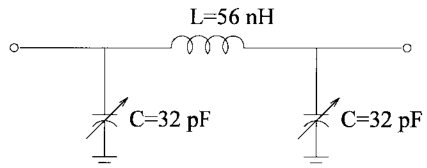


Fig. 4. Circuit schematics of the third-order LPF.

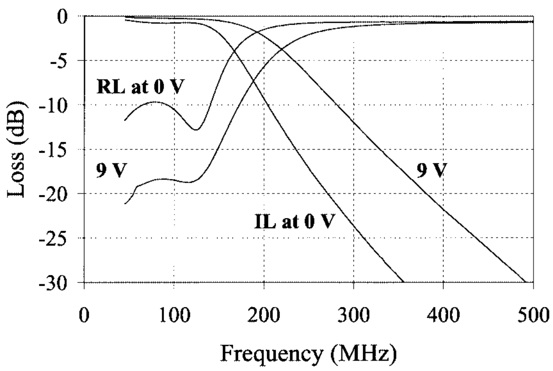


Fig. 5. Insertion and return losses of the third-order LPF with a change in the dc-bias voltage.

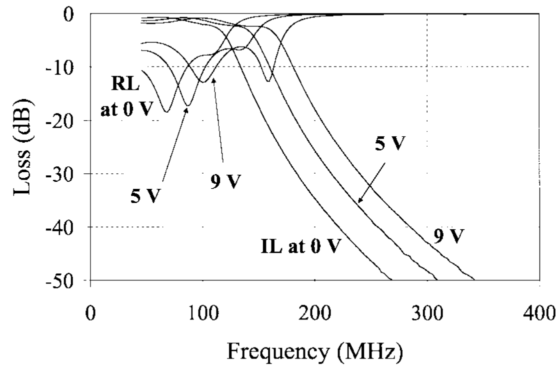


Fig. 6. Insertion and return losses of the fifth-order LPFs with a change in the dc-bias voltage.

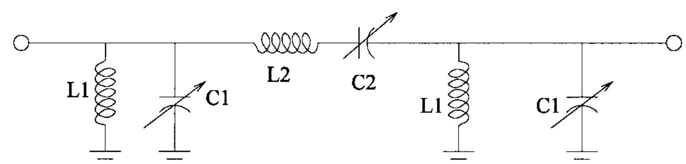


Fig. 7. Schematics of a third-order tunable BPF.

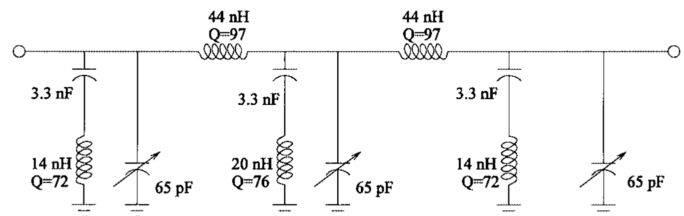


Fig. 8. Complete circuit of the tunable BPF (the quality factors of the inductors are given at 200 MHz).

higher quality-factor BST capacitors are expected. It should be mentioned that varactor diodes must be reverse biased by at least the peak value of the RF voltage amplitude for proper operation, which degrades their power-handling capability and tunability. On the other hand, this requirement is not present in BST-based capacitors, making them attractive for the design of high-power and tunable RF and microwave circuits.

III. BST Capacitor-Based Tunable Filters

A. Tunable LPFs

A lumped-element tunable LPF based on the third-order 0.5-dB ripple Chebyshev prototype was designed, as shown in Fig. 4. Thin bottom-electrode BST capacitors were used in the fabrication of the LPFs. The dc-bias voltage to the BST capacitors was applied through the ports of the filter using a bias tee. The BST portion was etched away using hydrofluoric acid (HF), and the access to the ground plane was obtained. The ground plane of the BST capacitors was then connected to the circuit using silver epoxy. Coilcraft 603CS type chip inductors were used in the fabrication of the LPFs. The top electrode of the parallel-plate BST capacitors were connected to the circuit using bond wires. An HP-8510C network analyzer was used to measure the filters. The LPF exhibited an insertion loss of 0.8 dB and a tunability of 30% (120–170 MHz), defined as the percentage change of the 3-dB cutoff frequency when the filter is tuned, with the application of 0–9 V dc, as shown in Fig. 5. The return loss of the filter within the passband was higher than 10 dB for all biasing conditions. A fifth-order tunable LPF was also fabricated. The design of this filter was approximate since the exact required BST capacitors were not available. This filter had an insertion loss of approximately 2 dB and a return loss of better than 7 dB with a 40% tunability by the application of 0–9-V dc bias, as shown in Fig. 6. The third-order intercept points (IP3s) of these filters were measured using a two-tone test setup. The output IP3 point for the third- and fifth-order LPFs were measured to be 24 and 22 dBm at 0-V dc bias with the application of two tones at 99.5 and 100.5 MHz, respectively.

B. Tunable BPF

A similar approach to the lowpass filter construction was followed to design and fabricate a tunable BPF. Multilayer ground-plane BST capacitors were used in the fabrication of the BPF. The circuit schematic of the designed filter is shown in Fig. 7. To simplify the fabrication of the BPF, J-inverters were used to transform the series *LC* circuit in Fig. 7 to a parallel *LC* circuit [27], shown in Fig. 8. To prevent the shunt inductors to short out the dc-bias voltage, decoupling capacitors were used in series with the inductors. However, series decoupling capacitors should also be added at the input and output of the filter to block the signal at low frequencies. A photograph of the BPF is shown in Fig. 9. The dc-bias voltage to the BST capacitors was again applied through the ports of the filter using a bias tee.

The measurement result for the BPF is presented in Fig. 10. The center frequency of the filter was tuned from 176 to 276 MHz, resulting in 57% tunability with the application of 0 –6-V dc. The BST capacitor tunability was 2.5 : 1 (60%) with the applied dc bias. The insertion loss within the passband

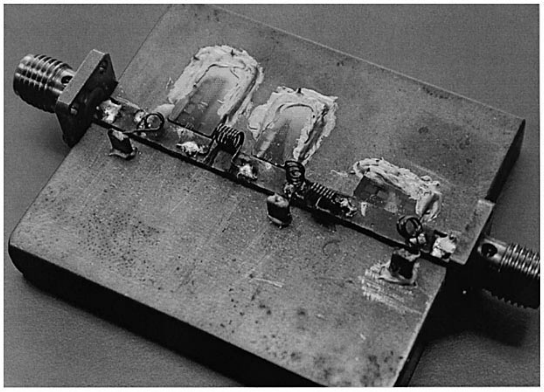
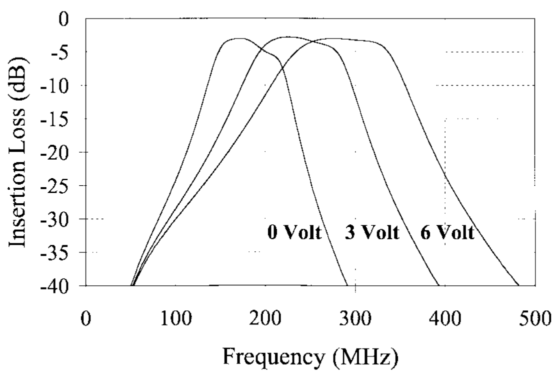
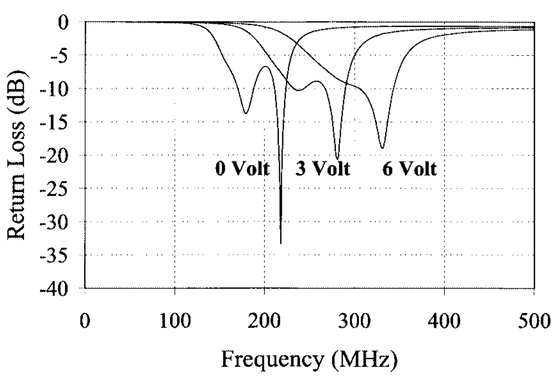


Fig. 9. Photograph of the constructed filter.



(a)



(b)

Fig. 10. (a) Insertion and (b) the return losses of the new BPF with the higher Q BST capacitors and inductors.

was 3 dB for all bias values. The return loss of the filter was measured to be better than 7 dB. By comparing the measured and simulated responses of the BPF, it was concluded that 1.5 dB of the 3-dB insertion loss is directly attributable to the BST capacitors. The remainder of the insertion loss (1.5 dB) is mostly due to the finite quality factor of the inductors and bond wires used. The insertion-loss performance achieved from this BPF is comparable to the commercially available varactor-diode-based tunable filters and switched-capacitor filter banks (Available second-order tunable BPFs based on varactor diodes and switched-capacitor filter banks with similar center frequency and bandwidth have an insertion loss of approximately 1 dB [28].) The shape factor of the BPF (defined as the ratio of the 30- to 3-dB bandwidth) was 2.85, which is also comparable to the commercial tunable BPFs. With the recent advances in BST film deposition and processing, lower insertion-loss BST-based tunable filters are expected. The output IP3 point of this filter was measured to be 19 dBm with the application of two tones at 169.5 and 170.5 MHz. This IP3 point is comparable to the IP3 points of varactor-diode-based tunable BPFs (Varactor-diode-based tunable filters have IP3 points of approximately $+10$ dBm [28].) Much higher IP3 points (30–50 dBm) are available from switched-capacitor filter banks due to the absence of nonlinear elements for tuning. Several approaches can be followed to improve the IP3 point of the BPF. Based on Agilent-ADS simulations, it was concluded that the major source of the intermodulation distortion is the high nonlinearity of the capacitance versus voltage (C–V) curve around 0-V dc bias, as shown in Fig. 1. Therefore, by applying a small dc bias to the BST capacitors, they can operate at a more linear region where the IP3 point is increased at the expense of reduced tunability. Another approach is to increase the BST thickness at the expense of requiring higher tuning voltages, which reduces the RF electric field across the capacitors, thereby improving the IP3. Furthermore, the design of the BPF can be optimized for the best IP3 performance without altering the filter response by simply adjusting the J-inverter parameter in the filter.

IV. Conclusion

A new metallization technique has been introduced, which has improved the quality factor of the BST capacitors by a factor of two. Tunable LPFs and BPFs based on parallel-plate BST capacitors have been presented. The LPF achieved 40% tunability with the application of 0–9-V dc bias. The BPF showed 57% tunability with an applied dc bias of 0–6 V. The passband insertion loss of the BPF was measured to be 3 dB, which is a promising result compared to the commercially available varactor-diode-based tunable filters and switched-capacitor filter banks. The intermodulation distortion generated by the filters was also reported. The IP3 point of the BPF is comparable to the IP3 points of the commercially available varactor-diode-based tunable filters.

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