

Analog Tunable Matching Network Using Integrated Thin-Film BST Capacitors

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Abstract— This paper presents an electronically tunable impedance transformer and matching network for RF applications, utilizing thin-film Barium Strontium Titanate (BST) tunable capacitors in an integrated-passive network on sapphire. The impedance transformer can be electronically varied from a 4:1 to 2:1 transformation in a 50 Ohm environment. A slight modification of this circuit is shown to provide a match for a highly-reactive integrated antenna allowing the antenna to be used with improved efficiency from 420MHz to 500MHz. ACPR measurements are presented on the latter network showing ACPR1 of >50dBc at 27dBm drive power.

I. INTRODUCTION

Thin film $\text{Ba}_x\text{Sr}_{(1-x)}\text{TiO}_3$ (BST) is a high-permittivity dielectric material with a remarkably large variation in dielectric constant with applied field [1]. Parallel-plate capacitors with thin-film BST have achieved as much as a 6:1 change in dielectric constant in laboratory demonstrations. High-quality BST has been successfully deposited on a number of commercially viable substrates using many different deposition methods [2-4]. BST capacitors with a large tuning range and low RF loss can be obtained by optimizing the growth conditions of the film [5] and the circuit layout geometry [6]. Unlike varactor diodes, BST capacitors do not have a forward conduction region and hence can support a large AC voltage swing at low bias voltages, which makes them attractive for applications in RF front ends, for example in amplifier output matching networks.

Recently BST capacitors have been exploited to demonstrate low-cost microwave and mm-wave phase-shifters and tunable filters [7-8]. In this paper, we describe the integration of BST capacitors in a commercial thin-film process, and a first demonstration of the devices in a tunable integrated matching network. The thin-film process includes other passive components such as thin-film resistors, fixed capacitors, and spiral inductors, on sapphire substrates. The matching network is demonstrated in a fixed-bandwidth impedance-transforming application, and a frequency-selective match to a highly reactive load (antenna). In both

cases, the objective is to exploit the analog tunability to improve overall circuit efficiency, so the design for low-loss is essential. Issues affecting RF loss and linearity performance are discussed, and the linearity is explored using ACPR measurements with a CMDA waveform.

II. BST CAPACITOR MODELING

The BST material used in this work was deposited by RF magnetron sputtering at elevated temperatures on sapphire substrates, using Pt-based electrodes. Growth conditions are similar to those presented in [3-5]. Material thickness for the BST process are on the order of 100-300nm depending on the application and voltage-tuning requirements. A typical tuning curve for an integrated parallel-plate structure is shown in fig. 1, showing the dependence of both capacitance and dielectric loss (inverse loss tangent) on bias voltage. For this particular material a 2.7:1 change of capacitance with $\tan\delta < 0.01$ was obtained with bias voltages ranging from 0 to 15volt, Typical DC breakdown for such a device is $\sim 30\text{V}$. The zero-bias

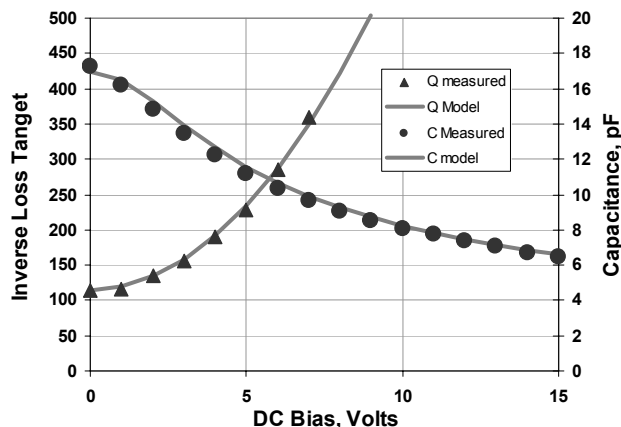


Fig. 1. Representative tuning curves at 1MHz for thin-film BST varactors,

dielectric constant for the films is typically around 250, yielding a high capacitance density of $\sim 20\text{fF}/\mu\text{m}^2$. This allows for the integration of high-value on-chip bypass or blocking capacitors in our process.

For design purposes it is important to have an accurate RF model for the varactors. A simple model that captures the

critical loss elements and the large-signal properties of the BST capacitors is shown in fig. 2. The material nonlinearities are described by the parallel combination of $G(V)$ and $C(V)$. An empirical model that adequately describes the C-V and Q-V tuning curves of fig. 2 is given by

$$C(V) = \frac{C_0}{\sqrt[3]{1 + (V/V_m)^2}} \quad G(V) = \frac{\omega C(V)}{Q_{BST}(V)} \quad (1)$$

$$Q_{BST}(V) = \frac{1}{\tan \delta} = Q_0(1 + qV^2)$$

where C_0 , V_m , Q_0 and q are fitting parameters. This model is overlaid with measured data in fig. 1 showing excellent agreement. The film thickness and material composition (Ba/Sr ratio) are primary factors in determining the tunability

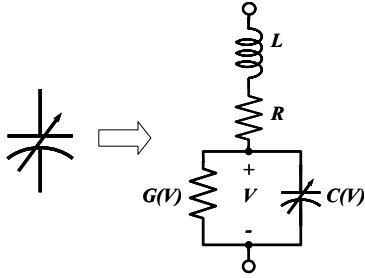


Fig. 2. The device model used for design and simulations.

at a given voltage and hence V_m . The film quality factor Q_{BST} can be determined from low-frequency (1 MHz) impedance measurements or by extrapolating on-wafer RF data to low frequencies.

The high-frequency loss of a thin film (MIM) capacitor depends on both the loss tangent of the dielectric and the conductor loss of the metal layers, modeled by the series resistance R in fig. 2. We can associate a Q-factor with conductor loss alone, denoted as Q_c , in which case the overall Q-factor of the device and series resistance can be written as

$$\frac{1}{Q_{total}} \approx \frac{1}{Q_c} + \frac{1}{Q_{BST}} \quad R = \frac{1}{\omega Q_c C} \quad (2)$$

The series resistance is dependent on the metalization scheme and layout geometry [6], and can be determined by fitting broadband RF data to the model of fig. 2 and extracting the material losses from the total device loss as in (2).

The series inductance is easily determined by measurement of the self-resonant frequency of the varactor, but care must be taken to first remove stray reactive parasitics arising from on-wafer probe contacts.

III. VARIABLE IMPEDANCE TRANSFORMER NETWORK

Using the BST varactor model, a simple matching network was designed to transform a 50Ω load to lower impedances in the 850~950MHz range. The circuit diagram is shown in Figure 3. Inductor L_1 was realized with a high-Q ($Q \sim 60$) off-chip SMT air-core inductor. All other components – tunable BST capacitors, DC-blocking capacitors, biasing resistors, and bond pads – were fabricated monolithically in a $\sim 0.7 \times 0.8$ mm

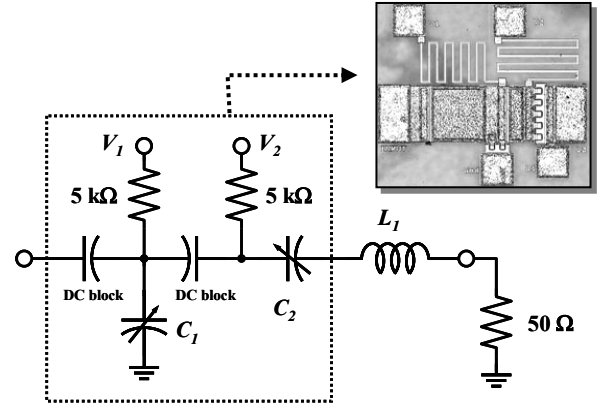


Figure 3 – Impedance transformer schematic, and photo of the die (chip size: 0.7mm x 0.8mm).

Table 1 – Measured data for the BST-based impedance transformer

V_1 (volts)	0	3.5	7	10.5	14
V_2 (volts)	8	6.25	4.5	2.75	1
Zin @ 900MHz	13	15	20	25	29
Insertion loss (dB)	0.28	0.28	0.26	0.25	0.24

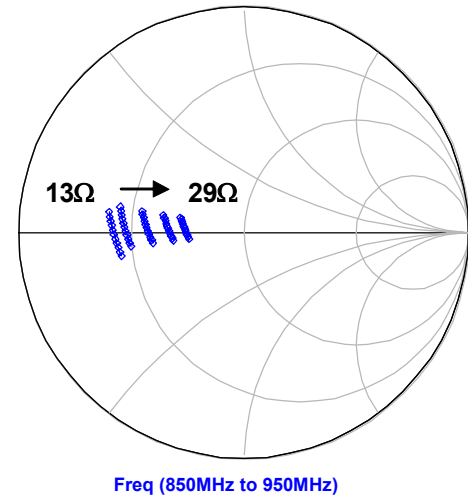


Fig. 4. Measured output impedance of the impedance transformer overall several bias states, across the 800-900MHz band.

die on sapphire in commercial foundry. V_1 and V_2 are the DC control voltages for capacitor tuning. The BST chip and the inductor were mounted on a FR4 test board.

Table 1 shows the relationship between representative control voltages and the resulting input impedance of the impedance transformer when terminated with 50Ω . The insertion loss of the network is below 0.3dB over all bias states, and the output impedance varies continuously between 13Ω and 29Ω at 900MHz (Figure 4). Hence the impedance transformation ratio can be changed by a factor of two, from $\sim 3.8:1$ to $1.7:1$.

IV. TUNABLE ANTENNA MATCH

A matching network design usually involves a trade-off between bandwidth and loss. Broadband matching for devices

or circuits with large reactance inevitably have more loss hence less efficiency. However, by designing a narrowband matching network with tunable center frequency, operation over multiple bands and high efficiency characteristics can be achieved at the same time.

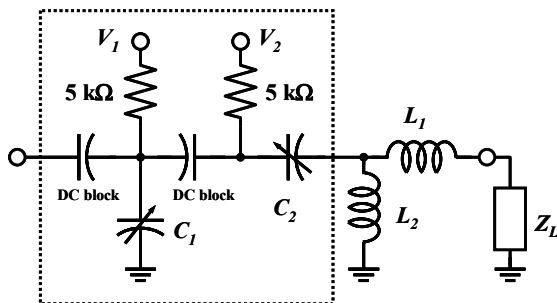


Fig. 5. Adaptation of the circuit of fig. 3 to implement a tunable match for a highly-reactive electrically-small antenna.

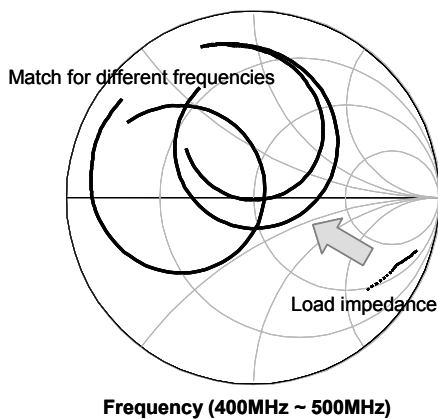


Fig. 6. Measured impedance for an electrically-small antenna along with simulated performance of the matching network shown in fig. 5.

Figure 5 shows an adaptation of the matching network of fig. 3 to implement a tunable matching network for an electrically-small antenna element operating at a nominal center frequency of 450MHz. Due to the large capacitive reactance of the antenna, a fixed matching network with low loss would result in a narrow operating bandwidth. The design objective was to implement a tunable match to allow the antenna to be operated from 420MHz to 500MHz with high efficiency. Fig. 6 shows the measured impedance of the antenna, along with the simulated performance of the circuit at three different bias states. Fig. 7 shows the measured insertion loss performance at three different bias states. Using the tunable matching network the antenna circuit, the operating frequency can be tuned between 420MHz to 500MHz with overall efficiency of >85%.

Linearity of the matching network for medium-power applications was examined by measuring ACPR with a CDMA IS-95 waveform at 27dBm input power. An Agilent xxx wideband signal analysis system was used for this measurement. The results are shown in fig. 8. An ACPR1 of >50dBc was determined from this measurement.

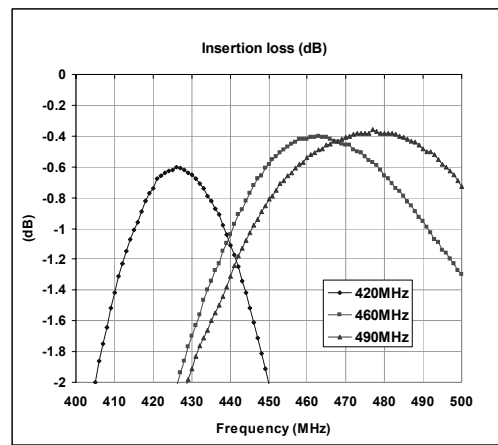


Fig. 7. Tuning the operational frequency of the circuit.

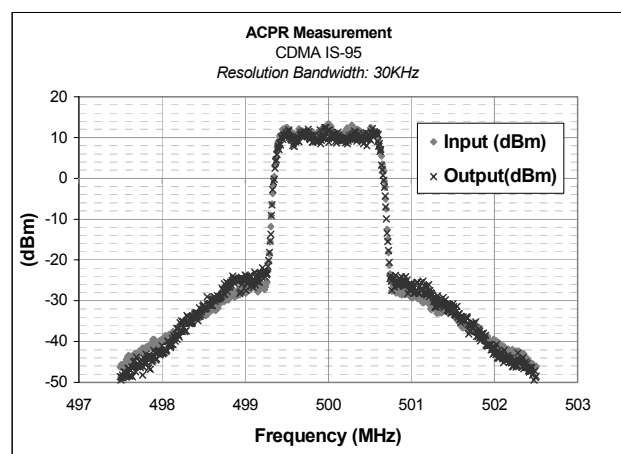


Fig. 8. ACPR measurements

V. CONCLUSION

In this paper, the implementation of two analog tunable matching networks was described, using an integrated BST capacitor process. An impedance transformer was implemented to provide a variable impedance transformation ratio of 3.8:1 to 1.7:1 in a 50Ω system. By adding a n addition off-chip high-Q inductor, the same matching network was adapted to a tunable antenna matching application, allowing a highly-reactive electrically-small antenna to be operated over a 420-500MHz band with >85% efficiency. This technology shows promise for addressing many front-end matching problems in modern RF systems.

REFERENCES

- [1] B. Acikel, P. Hansen, T.R. Taylor, A.S. Nagra, J. S. Speck, and R.A. York, "Tunable Strontium Titanate thin-films for Microwave Devices," *Journal of Integrated Ferroelectrics*, vol. 39, pp.291-298, 2001
- [2] C. Basceri, S.K.Streiffer, A. I.Kingon, and R. Waser, "The dielectric response as a function of temperature and film thickness of fiber-textured (Ba,Sr)TiO3 thin-films grown by chemical-vapor deposition", *J. Applied Phys.*, vol. 82, pp. 2497-2504, Sept. 1997
- [3] R.A. York, A.S. Nagra, P. Periaswamy, O. Auciello, S.K. Streiffer and J. Im, "Synthesis and Characterization of (Ba_xSr_{1-x})Ti_{1+y}O_{3+z} Thin Films

- and Integration into Microwave Varactors and Phase Shifters,” *Journal of Integrated Ferroelectrics*, vol. 34, pp.177-188, 2001
- [4] B. Acikel, Y. Liu, A.S. Nagra, T.R. Taylor, P.J. Hansen, J.S. Speck, and R. York, “Phase Shifters using (Ba,Sr)TiO₃ Thin Films on Sapphire and Glass Substrates,” *IEEE International Microwave Symposium Digest, IMS 2001*, May 2001, pp. 1191-1194
- [5] T. R. Taylor, P. J. Hansen, B. Acikel, N. Pervez, R. A. York, and J. S. Speck, “The influence of stoichiometry on the dielectric properties of sputtered strontium titanate thin films” To appear in *Journal of Applied Physics*, vol. 93, no. 6, Sept 2003
- [6] R.A. York, A.S. Nagra, E. Erker, T. Taylor, P. Perisawamy, J. Speck, S. Streiffer, D. Kaufmann, and O. Auciello, “Microwave Integrated Circuits Using Thin-film BST,” *Proc. Of 12th annual International Symp. on Applications of Ferroelectrics*, vol. 1, pp. 195-200. 2001
- [7] B. Acikel, T.R. Taylor, P.J. Hansen, J.S. Speck, R.A. York, “A new High Performance Phase Shifter using Ba_xSr_{1-x}TiO₃ thin films,” *IEEE Microwave and Wireless Components Lett.*, vol. 12, pp. 237-239, July 2002
- [8] A. Tombak, J-P. Maria, F.T. Ayguavives, J. Zhang, G.T. Stauf, A. Kingon, A. Mortazawi, “Voltage-controlled RF filters employing thin-film barium-strontium-titanate tunable capacitors”, *IEEE Trans. Microwave Theory Tech.* , Vol. 51, pp. 462-467, Feb 2003