A New High Performance Phase Shifter using $Ba_xSr_{1-x}TiO_3$ Thin Films

Baki Acikel, Troy R. Taylor, Peter J. Hansen, James S. Speck, and Robert A. York

***Abstract*—In this paper, a new device topology has been proposed to implement parallel plate capacitors using $Ba_xSr_{1-x}TiO_3$ (BST) thin films. The device layout utilizes a single parallel capacitor and minimizes conductor losses in the base electrode. The new design simplifies the monolithic process and overcomes the problems associated with electrode patterning. An X-Band 180° phase shifter has been implemented using the new device design. The circuit provided 240° phase shift with an insertion loss of only 3 dB at 10 GHz at room temperature. We have shown a figure of merit 93°/dB at 6.3 GHz and 87°/dB at 8.5 GHz. To our knowledge, these are the best figure of merit results reported in the literature for distributed phase shifters implemented using BST films at room temperature.**

***Index Terms*—$BaSrTiO_3$, distributed circuits, ferroelectric varactors, parallel plate capacitors, phase shifters, voltage controlled delay lines.**

I. Introduction

MODERN phase array systems require a large number of expensive phase shifters. Therefore, low loss and low cost microwave phase shifters are required to improve performance and reduce the cost of phase arrays to ensure widespread application. $Ba_xSr_{1-x}TiO_3$ (BST) thin films have been investigated as a potential low cost voltage tunable element for microwave circuit applications because of their high tunability, relatively low loss, and fast switching speed. Several groups [1]–[4] have implemented phase shifters using BST thin films. In some of these applications [1], [2], BST forms the entire substrate on which the conductors are deposited resulting in high control voltages and ineffective use of the BST film. Our approach has been to periodically load a coplanar waveguide transmission line with tunable BST capacitors [3], [4]. Biasing BST varactors alters the phase velocity of the transmission line, providing necessary phase shift.

Both interdigital and parallel plate capacitors can be used for loading the transmission line [4]. The parallel plate structures use the film tunability more efficiently and require much lower bias voltages than interdigital varactors since the electric fields are better confined in the film. Phase shifters on different substrates have been reported [4]. In all of these circuits, the parallel plate capacitors involved an elaborate process and required bottom electrode patterning. Patterning the bottom electrode typically limits the maximum bottom electrode thickness the process can accommodate. These circuits had two parallel plate capacitors connected in series, which effectively doubled the required tuning bias voltages [3], [4].

In this paper, a new device topology has been proposed to implement parallel plate capacitors. The device layout uses a single parallel capacitor and minimizes conductor losses in the base electrode. An X-Band 180° phase shifter has been demonstrated using this new device layout.

A. Device Fabrication

A parallel plate capacitor consists of a dielectric film sandwiched between bottom and top electrodes. For voltage tunable BST varactors, ferroelectric thin films are grown on the bottom electrode on a substrate [Fig. 1(a) and (b)]. One of the biggest challenges of BST growth on different substrates is finding the suitable electrode stacks for the bottom electrode, appropriate for parallel-plate devices, which will survive the high growth temperatures of BST and maintain good adhesion during subsequent processing. In this work, BST thin film was grown on pre-patterned sapphire substrate that had ebeam evaporated Au/Pt metals as the bottom electrode stack. Au metal was incorporated in to the base electrode to increase the conductivity and reduce the ohmic losses. Sapphire was chosen as a substrate because it has good insulating properties and low loss tangent. These substrates are also relatively inexpensive. The BST films used were grown using rf magnetron sputtering. The film stoichiometry was optimized for the tunability and microwave loss performance. A low-Barium BST film composition ($Ba_{0.2}Sr_{0.8}TiO_3$) was grown (2800 Å) for good loss performance. Pt/Au top electrodes were evaporated followed by BST etch. Thick Au metallization was done for CPW structures. A picture of a completed parallel plate capacitor is shown in Fig. 1(a) together with a schematic side view of the structure in Fig. 1(b). The picture of distributed phase shifter circuit is also shown in Fig. 1(c). As can be seen from the device layout, the series resistance associated with the BST capacitor has contributions from both the base and top electrodes. Thick metal contacts to the base electrode on each side of the top electrode allows for reduced resistance due to the base electrode. Therefore, the thick Au metal contacts should be brought as close to the top electrode as possible to decrease resistance contribution from the base electrode. To first order, the base electrode contribution depends on the device periphery, whereas the top contact resistance depends on aspect ratio.

B. Phase Shifter Circuit and Measurements

The phase shifter circuit basically consists of a high impedance transmission line periodically loaded with thin film

Manuscript received December 5, 2001; revised April 22, 2002. This work was supported by DARPA through the Frequency Agile Materials for Electronics program (FAME) under Award DABT63-98-1-0006 The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

B. Acikel and R. A. York are with the Electrical and Computer Engineering Department, University of California, Santa Barbara, CA 93106 USA.

T. R. Taylor, P. J. Hansen, and J. S. Speck are with the Materials Department, University of California, Santa Barbara, CA 93106 USA.

Publisher Item Identifier 10.1109/LMWC.2002.801129.

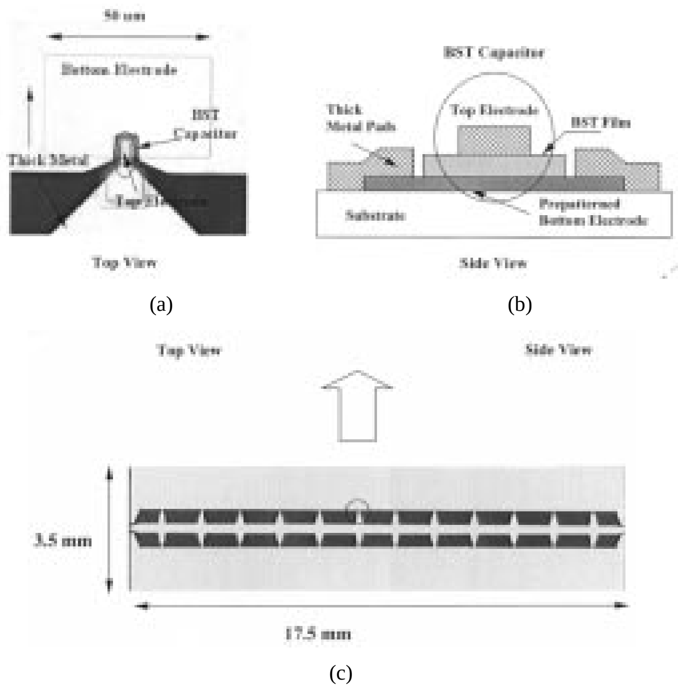

Fig. 1. (a)–(c) Photographs of the new BST parallel plate device layout—top and side view—and the distributed phase shifter circuit. Phase shifter is consisted of 12 identical sections loading CPW line.

BST capacitors as described in [4], [5]. Well below the Bragg frequency, the structure behaves like a synthetic transmission line. By applying bias, it is possible to tune the capacitance value of the BST capacitors, thus varying the phase velocity and characteristic impedance of the line. The phase shifter presented here was designed to provide 180° phase shift at 10 GHz. The Bragg frequency for the periodically loaded line was chosen to be 17.5 GHz, well above operating frequency. The loading BST capacitors have a zero bias capacitance of about 256 fF. To preserve the symmetry, two 128 fF BST capacitors were connected in parallel from the CPW center conductor to both ground planes. Fig. 1(c) shows the distributed phase shifter circuit with twelve identical loaded sections.

RF measurements were made on a HP8722D network analyzer that was calibrated using on-wafer standards. The two-port s-parameters of the phase shifter circuit were recorded up to 10 GHz for different bias voltages. Fig. 2(a) and (b) shows the insertion loss and return loss of the phase shifter circuit at different biases. The maximum insertion loss is measured to be only 3 dB at 10 GHz. The return loss is better than −10 dB for all states from DC to 10 GHz. The differential phase shift with respect to the zero bias is plotted in Fig. 3. The circuit was capable of a 0–240° continuous phase shift at 10 GHz. This corresponds to a figure of merit of 80°/dB, which is defined by the differential phase shift divided by the maximum insertion loss for zero voltage state, at the operating frequency. The maximum bias voltage required to get this phase shift was below 20 V, which is smaller almost by a factor of two than a similar phase shifter with the same BST composition and thickness that had two capacitors in series configuration [4]. The circuit has demonstrated a record figure of merit 93°/dB at 6.3 GHz and 87°/dB at 8.5 GHz.

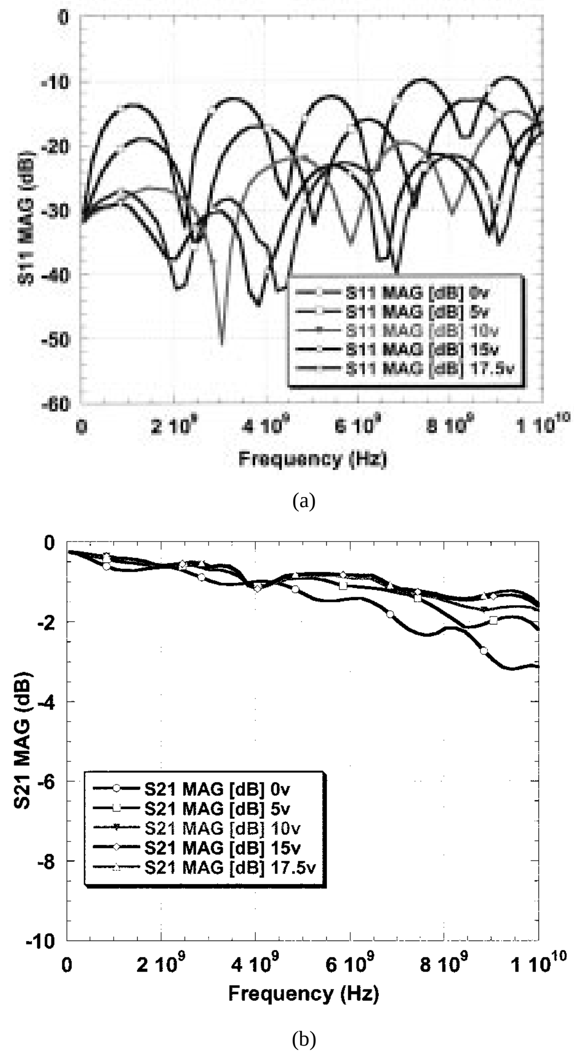

Fig. 2. (a), (b) Return and insertion loss of the circuit. Insertion loss was only 3 dB at 10 GHz. Return loss was better than −10 dB for all bias states up to 10 GHz.

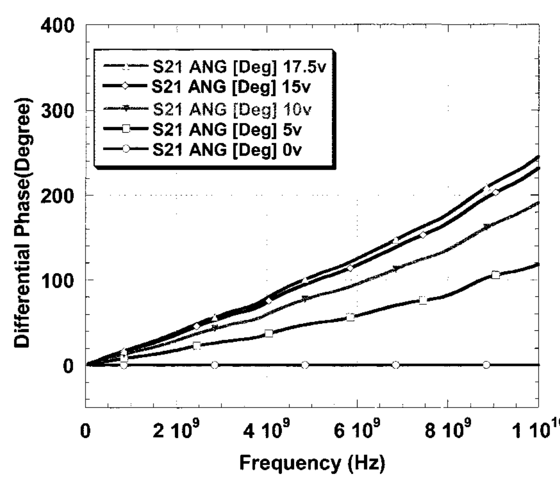

Fig. 3. Differential phase shift at different bias voltages as a function of frequency. Phase shifter provided 240° phase shift at 10 GHz.

For the characterization of the circuit and BST capacitors at microwave frequencies, parallel plate capacitors were fabricated with values of 0.15 pf–2pF. The one-port S_{11} measurements were made on test structures that were mounted at the end of CPW lines at different bias voltages. The s-parameters are recorded up to 10 GHz. Discrete capacitor and thin film properties were extracted using an equivalent circuit model as outlined in [6] using open and short circuit structures on the wafer to account for the pads and parasitics correctly. Discrete capacitors showed a tunability of $2.5:1$.

The primary limiting factor in insertion loss for these circuits is the BST film and electrode losses. Using thicker bottom electrodes would decrease the conductor losses further. Transmission line losses can be made even smaller by using a glass substrate, which has a lower dielectric constant.

II. Conclusion

In this paper, a new type of parallel plate capacitor using $Ba_xSr_{1-x}TiO_3$ (BST) thin film has been implemented for phase shifter applications. An X-band distributed phase shifter fabricated using this new process provided 240° phase shift with an insertion loss of only 3 dB at 10 GHz at room temperature. The circuit has demonstrated a record figure of merit 93°/dB at 6.3 GHz and 87°/dB at 8.5 GHz at room temperature. This new device design simplifies the fabrication process and overcomes some of the difficulties such as electrode patterning. Low voltage (below 20 V) operation and compatibility with monolithic process are other advantages of the phase shifter. The circuit performance can be improved further by lowering the BST film and conductor losses and increasing device tunability.

References

[1] V. K. Varadan, K. A. Jose, V. V. Varadan, R. Hughes, and J. F. Kelly, "A novel microwave planar phase shifter," *Microwave J.*, pp. 244–54, Apr. 1995.

[2] F. De Flaviis, N. G. Alexopoulos, and O. M. Stafsudd, "Planar microwave integrated phase-shifter design with high purity ferroelectric material," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 963–969, June 1997.

[3] E. G. Erker, A. S. Nagra, Y. Liu, P. Periaswamy, T. R. Taylor, J. Speck, and R. A. York, "Monolithic Ka-band phase shifter using voltage tunable $BaSrTiO_3$ parallel plate capacitors," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 10–12, Jan. 2000.

[4] B. Acikel, Y. Liu, A. S. Nagra, T. R. Taylor, P. J. Hansen, J. S. Speck, and R. A. York, "Phase shifters using $BaSrTiO_3$ thin films on sapphire and glass substrate," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2001, pp. 1191–1194.

[5] A. S. Nagra and R. A. York, "Distributed analog phase shifters with low insertion loss," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1705–1711, Sept. 1999.

[6] K. Ikuta, Y. Umeda, and Y. Ishii, "Measurement of high frequency dielectric characteristics in the mm-wave band for dielectric thin films on semiconductor substrates," *Jpn. J. Appl. Phys.*, vol. 34, pp. L1211–L1213, 1995.