A New X Band 180^O High Performance Phase Shifter using $(Ba,Sr)TiO_3$ Thin Films

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Absract — **In this paper, a new device topology has been proposed to implement parallel plate capacitors using $BaSrTiO_3$ (BST) thin films for microwave applications. The new device design simplifies the monolithic process and overcomes the problems associated with electrode patterning. An X-Band 180° phase shifter has been implemented using new device layout. The circuit provided 240°-phase shift with an insertion loss of only 3 dB at 10GHz 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 state of the art results for distributed phase shifters implemented using parallel plate or interdigital capacitors at room temperature.**

I. INTRODUCTION

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. 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].

II. DEVICE FABRICATION

Ferroelectric thin films are grown on the bottom electrode on a substrate. One of the biggest challenges of BST growth on different substrates is finding the suitable electrode stacks for the bottom electrode, 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 Au/Pt metals as the bottom electrode stack. Au metal was incorporated to the base electrode to increase the conductivity and lower 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. 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. 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. To first order, the base electrode contribution depends on the device periphery whereas the top contact resistance depends on aspect ratio. Therefore thick metal contacts to the base electrode on each side of the top contact allows for reduced resistance due to the base electrode.

II. X-BAND 180^O PHASE SHIFTER

A. Circuit Layout

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

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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

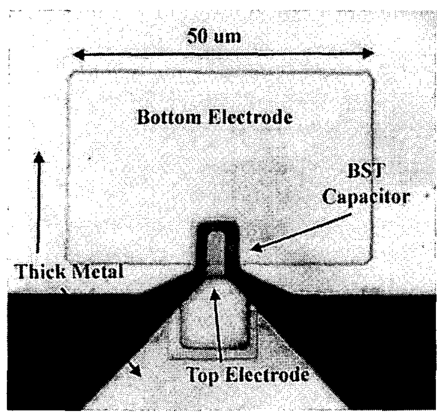

Fig. 1. A picture of the new BST parallel plate capacitor device design used to load the transmission line periodically.

have a zero bias capacitance of about 256fF. To preserve the symmetry, two 128fF BST capacitors were connected in parallel from the CPW center conductor to both ground planes.

B. Measurement Results

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. The differential phase shift with respect to the zero bias is plotted in Fig. 2a. The circuit was capable of a 0-240° continuous phase shift at 10 GHz. Fig. 2b shows the insertion loss and return loss of the phase shifter circuit at different biases. The maximum insertion loss is measured to be only 3dB at 10GHz. The return loss is better than -10 dB for all states from DC to 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 20V, which is smaller 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.

For the characterization of the circuit and BST capacitors at microwave frequencies, parallel plate capacitors were fabricated with values of 0.15pf-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

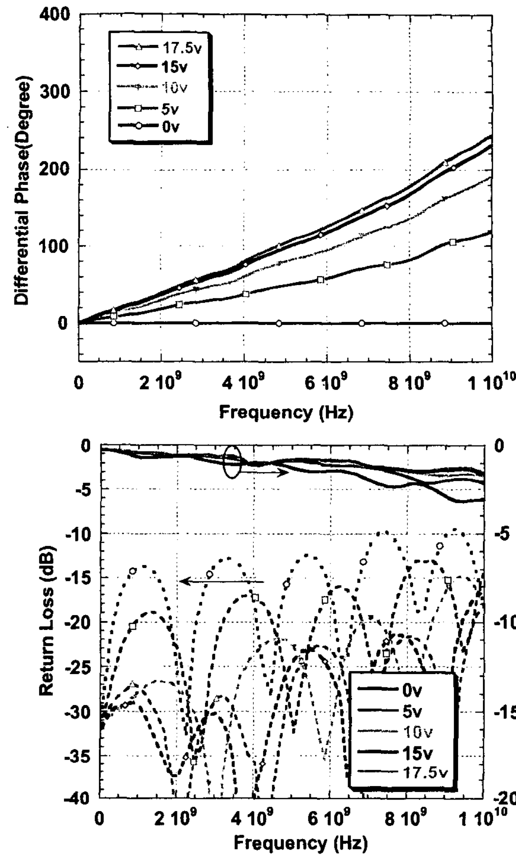

Fig. 2a-b. The phase shifter circuit has provided a phase shift of 240° at 10 GHz. The insertion loss was only 3 dB at the operating frequency and return loss was better than 10 dB for frequencies up to 10 GHz.

The primary limiting factor in insertion loss for the circuit 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 because of its low dielectric constant.

IV. Conclusion

In this paper, a new type of parallel plate capacitor using BaSrTiO3 (BST) thin film for phase shifter applications has been proposed. This new device design simplifies the process and overcomes the difficulties related to electrode patterning. The device layout also minimizes conductor losses due to the bottom electrode. An X-band distributed phase shifter fabricated using this new process provided 240°- phase shift with an insertion loss of only 3 dB at 10GHz at room temperature. The circuit has demonstrated

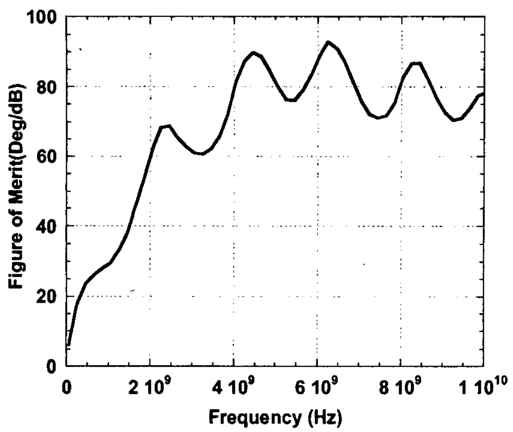

Fig. 3. The figure of merit for the phase shifter is shown. The best figure of merit is 93 °/dB at 6.3 GHz.

a record figure of merit 93°/dB at 6.3 GHz and 87°/dB at 8.5 GHz at room temperature. Low voltage (below 20V) operation and compatibility with monolithic process are other advantages of the phase shifter. Lowering the film and conductor losses and increasing device tunability can improve the circuit performance further.

ACKNOWLEDGEMENT

This research has been supported by DARPA through the Frequency Agile Materials for Electronics program (FAME) under Award No. DABT63-98-1-0006

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