Phase Shifters using (Ba,Sr)TiO_3 thin films on Sapphire and Glass Substrates

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Abstract — **In this paper, we present results from distributed phase shifter circuits that were fabricated on sapphire and glass substrates. The circuits employ voltage tunable (Ba,Sr)TiO_3 (BST) thin films deposited by rf magnetron sputtering. Both parallel-plate and interdigital capacitor structures are investigated. K/Ka-band phase shifters demonstrated a phase shift of 265^o with an insertion loss of 5.8 dB at 20 GHz and 180^o phase shift with an insertion loss of 4 dB at 30 GHz. Both circuits demonstrated a promising figure of merit ~60^o/dB at 10GHz. A C/X-band phase shifter demonstrated a phase shift of >460 degrees with an insertion loss of 8.8 dB at 8GHz.**

I. Introduction

Phase shifters are crucial components in modern phased array antenna systems. Low-loss and inexpensive microwave phase shifters are required to improve performance and reduce the cost of these systems to ensure widespread application. $Ba_xSr_{1-x}TiO_3$ (BST) thin films have a promising potential as voltage tunable elements in phase shifter applications because of their high tunability, relatively low loss, and fast switching speed. In addition, the films can be deposited inexpensively using sputtering or MOCVD and processed using monolithic fabrication.

Several groups [1]-[6] have investigated the development of BST-based phase shifters. In some demonstrations [1]-[2], BST forms the entire substrate on which the conductors are deposited resulting in high control voltages and ineffective use of BST film Our approach was to periodically load a coplanar wave guide transmission line with tunable BST capacitors [7]. The circuit presented in [5] was implemented on a high resistivity silicon substrate and showed a figure of merit of ~27^O/dB at 30 GHz. The silicon substrate shows excessive losses and undesired leakage paths when biased, complicating the measurements and calibration. In this paper, we report BST phase shifters on highly insulating and low-cost glass and sapphire substrates. Preliminary measurement results on initial prototypes are reported in the following sections.

II. Device Fabrication

Sapphire and glass substrates were chosen because of good insulating properties and consequently low loss tangents. These substrates are also well accepted in the microwave industry and are relatively low cost. The BST films used in this work were grown using rf magnetron sputtering. The film stoichiometry was optimized for the tunability and microwave loss performance on the two substrates through manipulation of growth conditions.

A. Parallel-plate Structures

One of the biggest challenges for the BST growth on different substrates is finding suitable electrode stacks for the bottom electrode, appropriate for parallel-plate devices, that will survive the high growth temperatures of BST and maintain good adhesion during subsequent processing. In this work, a working solution involved the use of Pt on sapphire substrates, and Ti/Pt/Au electrode stacks on glass substrates. A low-Barium BST film composition ($Ba_{0.2}Sr_{0.8}TiO_3$) was grown (3100Å) for good loss performance. The circuits were fabricated using standard monolithic fabrication techniques Details of the fabrication can be found elsewhere [9]-[10].

For the characterization of BST films 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 40 GHz. The wafer also included open and short circuit structures to account for the pads and parasitics correctly. Discrete capacitor and thin film properties were extracted using an equivalent circuit model as outlined in [8]. Discrete capacitors showed a tunability of 2:1 with a quality factor of 30 at 20 GHz.

The parallel plate geometry provides a higher tunability at low voltages relative to interdigital capacitor structures since the electric fields are better confined in the film.

B. Interdigital Structures

Interdigital capacitors are less effective in tuning range but much easier in fabrication and are capable of high power operations. While glass substrate is a very good insulator and suitable for low leakage considerations, BST thin film sputtered directly on glass substrate demonstrates rather low tunability (<1.6:1). In our work, $Ba_{0.5}Sr_{0.5}TiO_3$ films were grown on c-axis sapphire substrate for higher tunability. The measured s-parameters were then used to extract the quality factor and the capacitance values. Interdigital capacitors showed a tunability of 2.2:1 with a quality factor of 20 at 10 GHz

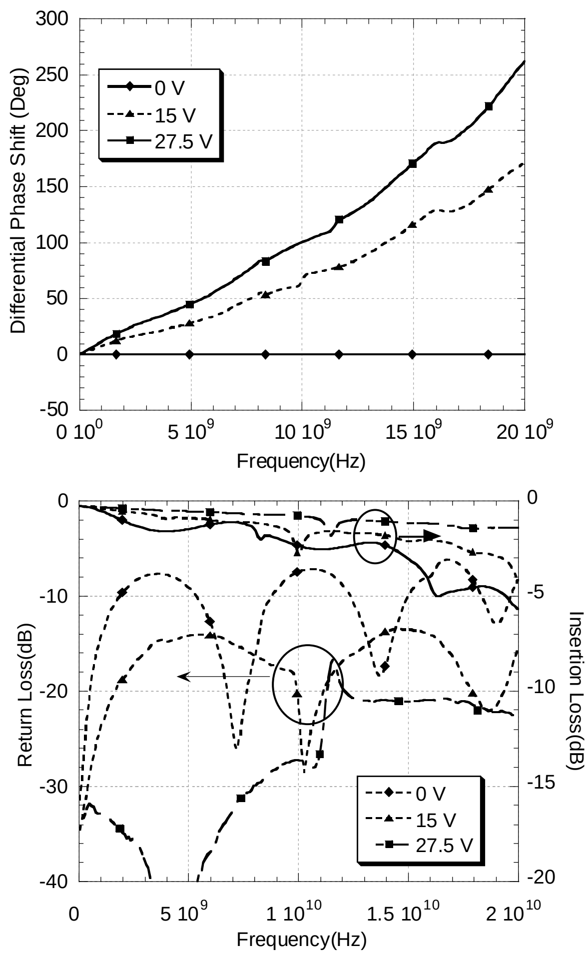

Fig. 1a-b Parallel-plate capacitor based phase shifter circuit results on sapphire. The circuit has provided a phase shift of 265^o with an insertion loss of 5.8 dB at 20 GHz.

III. Phase Shifter Results

The distributed phase shifter circuit design included a high impedance Z_i transmission line to be loaded periodically with voltage tunable BST capacitors (C_{var}), and spacing between the capacitors is denoted by L_{sect}. The desired differential phase shift can be achieved with minimum insertion loss for a given tunability using the optimum phase shifter design [7]. RF measurements were made using a HP 8722D network analyzer that was calibrated using on-wafer standards. The two-port s-parameters of the phase shifter circuits were recorded up to 40 GHz.

A. Parallel-plate Structures

Distributed-circuit delay lines using parallel-plate BST capacitors were designed for operation at K/Ka-band. To accommodate several circuits in a limited 2cm x 2cm die area, test structures were designed for 90 or 180 degrees of delay at 20GHz, assuming a 2:1 capacitance variation.

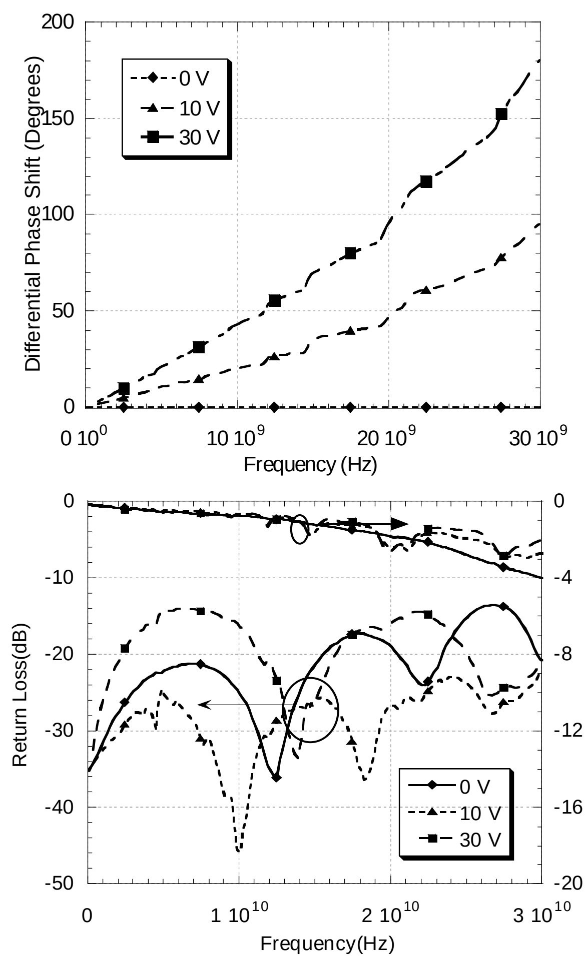

Fig. 2a-b Differential phase and s-parameters for the phase shifter on glass substrate.

Fig. 1a-b show the differential phase shift (normalized to the delay at zero bias) and insertion and return loss for the parallel-plate capacitor based circuit on the sapphire substrate for different bias values. The circuit was capable of continuous 0-265^o phase shift with an insertion loss of 5.8 dB at 20 GHz. Note that the return loss was relatively high at zero bias, a maximum of -7.5dB, which was a result of an unexpectedly high capacitance density in the films. Therefore, the results can be improved further by simply improving the impedance matching.

Fig.2a-b show measurement results for the parallel-plate delay circuit on glass substrates. The phase shifter provided a continuous phase shift of 180^O with an insertion loss of only 4dB at 30 GHz. In this case the return loss is less than -11dB for all states. Fig. 3 shows the figure of merit, which is defined by the differential phase shift divided by the maximum insertion loss for zero voltage state, for this circuit. The circuit shows a promising 60^o/dB around 10 GHz. Transmission line losses are smaller for glass substrate because it has a lower dielectric constant than sapphire. The primary limiting factor in insertion loss for these circuits is the BST device loss. Careful extraction of film parameters suggests that the low-Barium films have intrinsic quality-factors in excess of 100, therefore the total device loss is currently dominated by extrinsic factors such as electrode losses and other parasitics. We are currently attempting to identify the source of loss in these devices.

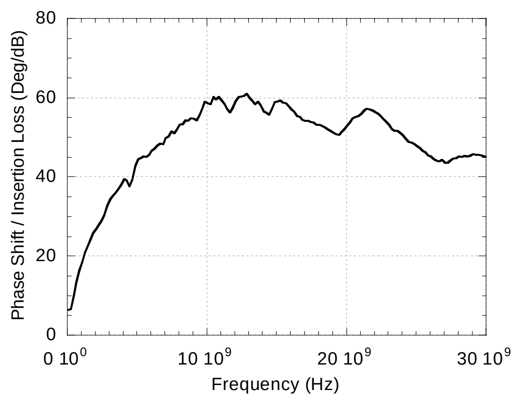

Fig. 3 Figure of merit for the glass substrate. 60^o/dB can be achieved at 10 GHz

B. Interdigital Structures

Delay-lines using interdigital capacitors were designed for C/X-band operation. In this case, we chose to fabricate a full-length delay line of >360 degrees at 10GHz, assuming a capacitance tunability of 1.6:1. Fig.4a-b shows the differential phase shift as a function of frequency for DC biases at 40V and 100V and the measured s-parameters of the phase shifter circuit at different DC biases. The measured circuit is capable of 0-460° phase shifts at 8GHz with a maximum insertion loss of only 8.8 dB. At 6.5GHz, continuous 0-360° phase shifts can be achieved with insertion loss of 7.2dB. The return loss is less than -10 dB over all phase states.

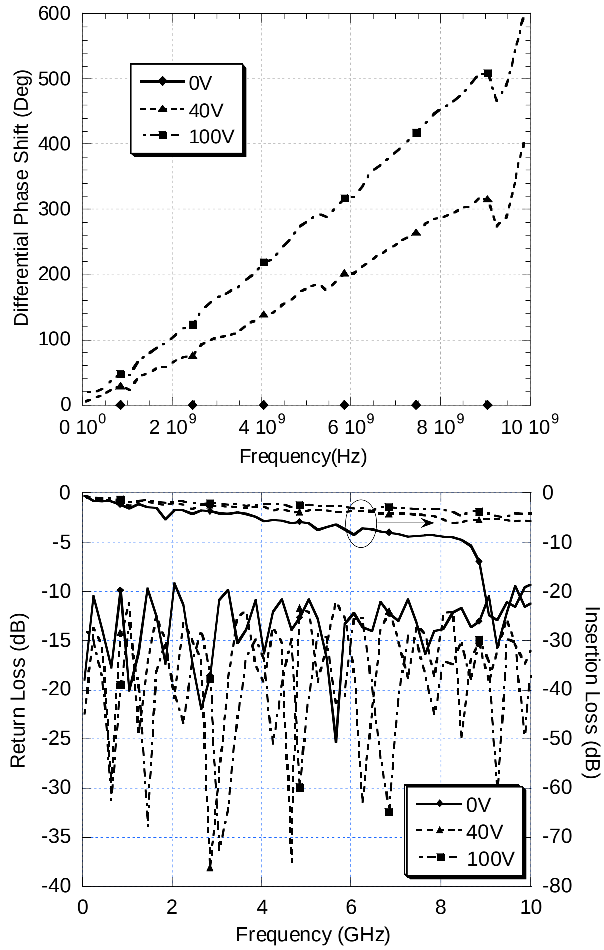

Fig. 4a-b Differential phase and s-parameters for the interdigital capacitor based phase shifter on sapphire substrate. The circuit demonstrated a phase shift of 460 degrees with an insertion loss of 8.8 dB at 8 GHz.

IV- CONCLUSION

Distributed phase shifters loaded by BST thin film parallel-plate and interdigital capacitors were fabricated on sapphire and glass substrates. K/Ka-band phase shifters provided 0-265^o phase shift with an insertion loss of 5.8dB at 20 GHz and 0-180^o with an insertion loss of 4dB at 30GHz,respectively. C/X-band phase shifter demonstrated a phase shift of 460 degrees with an insertion loss of 8.8 dB at 8GHz. The performance of phase shifters can be improved further by improving device tunability and lowering the microwave loss.

ACKNOWLEDGEMENT

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