

# Monolithic *Ka*-Band Phase Shifter Using Voltage Tunable BaSrTiO<sub>3</sub> Parallel Plate Capacitors

Erich G. Erker, Amit S. Nagra, Yu Liu, Padmini Periaswamy, Troy R. Taylor, James Speck, and Robert A. York

**Abstract**—A monolithic *Ka*-band phase shifter circuit that employs voltage tunable BaSrTiO<sub>3</sub> (BST) parallel plate capacitors is presented here. The circuit is capable of continuous 0°–157° phase shift at 30 GHz with an insertion loss of only 5.8 dB and return loss better than 12 dB. In addition to promising loss performance (27.1°/dB) at 30 GHz, the circuit reported here has several advantages over previously reported BST phase shifters such as moderate control voltages (20 V), room temperature operation, and compatibility with monolithic fabrication techniques.

**Index Terms**—Coplanar waveguides, delay lines, ferroelectric capacitors, ferroelectric films, millimeter-wave phase shifters, MIMIC's, varactors.

## I. INTRODUCTION

CURRENTLY, most phased array antenna systems rely on ferrite phase shifters and semiconductor device phase shifters. Ferrite phase shifters are slow to respond to control signals and cannot be used in applications where rapid beam scanning is required. Semiconductor device phase shifters have much faster response speeds, however their major drawback is that they have high losses at microwave and millimeter-wave frequencies. Another disadvantage with semiconductor phase shifters is that they have limited power-handling capability. Ferroelectric phase shifters have the potential to overcome all these limitations. Several groups [1]–[7] are investigating the possibility of implementing phase shifter circuits using barium strontium titanate (BST), which has an electric field tunable dielectric constant. In these circuits the ferroelectric material (BST) either forms the entire microwave substrate [1], [3] on which the conductors are deposited (thick films/bulk crystals) or a fraction of the substrate with thin BST films sandwiched between the substrate and the conductors [2], [4]–[7]. These circuits rely on the principle that since part or all of the microwave fields pass through the ferroelectric layer, the phase velocity of the waves propagating on these structures can be altered by changing the permittivity of the ferroelectric layer. This approach has several limitations: 1) the amount of capacitive loading due to the ferroelectric film cannot be easily varied to optimize phase shifter performance; 2) conductor losses are high in this structure due to the high dielectric

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constant of the ferroelectric film on which the transmission lines are fabricated; 3) the tunability of the film is not efficiently utilized; and 4) the control voltages required for this approach tend to be very high.

The approach proposed by us is different from the ones outlined above and relies on thin film BST (parallel plate) capacitors periodically loading a transmission line. When designed correctly [8]–[10] this structure behaves like a synthetic transmission line whose phase velocity can be controlled by changing the value of the external loading capacitors. The parallel plate capacitor topology utilizes the tunability of the BST film effectively and requires much lower control voltages. This is the reason why the circuit presented here only requires 20 V for maximum phase change as opposed to thick film/bulk phase shifter circuits [3]–[7] that require more than 100 V. The use of discrete BST capacitors makes it easy to control the amount of capacitive loading due to the ferroelectric film and thus allows the structure to be optimized for good loss performance [10]. Also, conductor losses are low in this topology since the transmission lines are fabricated on lower dielectric constant substrates such as silicon (high resistivity) as opposed to bulk ferroelectric substrates. Using this topology we have demonstrated phase shifter circuits with an insertion loss performance of 27.1°/dB at 30 GHz under room temperature operation. This is despite the fact that the quality factor of the BST capacitors used in the phase shifter circuits is currently quite low. With further improvements in BST capacitor quality factor (due to advances in BST processing and deposition techniques) the loss performance of these phase shifter circuits should be even better.

### A. Basic Principle and Circuit Design

The schematic of the proposed phase shifter circuit is shown in Fig. 1(a). The phase shifter basically consists of a high impedance transmission line (with characteristic impedance  $Z_i$  and phase velocity  $v_i$ ) that is periodically loaded with thin film Barium Strontium Titanate (BST) capacitors with spacing  $L_{\text{sect}}$ . For frequencies much below the Bragg frequency, this structure behaves like a synthetic transmission line [8]–[10] with modified propagation velocity and characteristic impedance. The properties of the synthetic transmission line depend on the inductance per unit length (which remains unchanged from that of an unloaded line) and the total capacitance per unit length (modified due to loading by BST capacitors). Since the capacitance value of the loading BST capacitors can be varied by applying bias, it is possible to change the phase velocity and impedance of the line. For the phase shifter application the value of the loading capacitors is chosen such

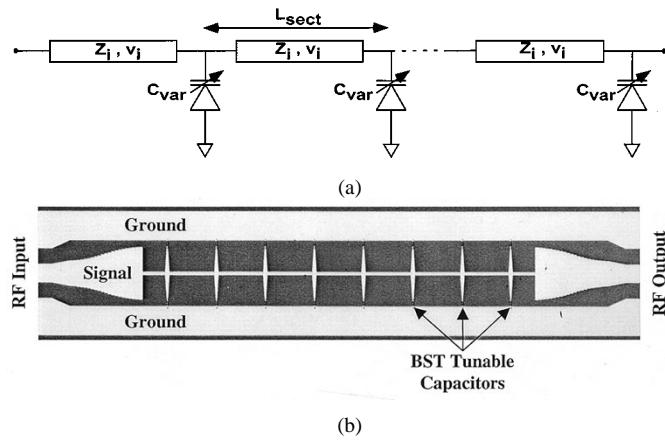


Fig. 1. (a) Circuit schematic of the phase shifter. (b) Photograph of the phase shifter circuit fabricated at UCSB.

that the impedance variation is small but by utilizing the correct number of sections the phase shift can be made as large as desired.

The *Ka*-band phase shifter circuit discussed here was fabricated on high-resistivity silicon using standard monolithic fabrication techniques. The design consisted of a CPW transmission line of characteristic impedance  $100\Omega$  fabricated on a high-resistivity silicon substrate ( $40\text{ K}\Omega\text{-cm}$ ). The CPW line was periodically loaded with BST capacitors whose zero bias capacitance was  $96\text{ fF}$ . The BST ( $150\text{ nm}$  thick) for the tunable capacitors was deposited by radio frequency (RF) magnetron sputtering. Platinum was used as the top and bottom electrode for the BST capacitors. The length of the unit cell (spacing between BST capacitors) was chosen to be  $340\text{ }\mu\text{m}$ , resulting in a Bragg frequency of  $55\text{ GHz}$ . In order to obtain a phase shift of  $160^\circ$  at  $20\text{ GHz}$ , nine identical cells were connected in series resulting in a total length of  $3.06\text{ mm}$ . CPW center conductor and gap dimensions of  $15$  and  $150\text{ }\mu\text{m}$ , respectively, were used here. In order to preserve the symmetry of the structure, the periodic loading capacitors were implemented using two devices of  $48\text{ fF}$  each (active area  $3\text{ }\mu\text{m}^2$ ), connected in parallel from the CPW center conductor to either ground plane, as shown in Fig. 1(b).

### B. Measurement Results

RF measurements were made on a HP 8722D network analyzer that was calibrated using on-wafer standards. The two-port S-parameters of the phase shifter circuit were recorded up to  $30\text{ GHz}$ . Fig. 2 shows the differential phase shift (with respect to the zero bias insertion phase) as a function of frequency for several bias values. As expected for a variable velocity transmission line, the circuit produced a phase shift that varied linearly with frequency (for frequencies well below the Bragg frequency). As the frequency approached the Bragg frequency the phase shift started to deviate from the linear response as explained in [10]. The circuit presented here was capable of continuous  $0^\circ$ – $157^\circ$  phase shift at  $30\text{ GHz}$  with any desired resolution. The maximum insertion loss at  $30\text{ GHz}$  occurred at zero bias and was only  $5.8\text{ dB}$  (see Fig. 3). The return loss was better than  $12\text{ dB}$  over all phase states as shown in Fig. 4.

The characteristics of the voltage-tunable BST capacitors were measured in order to model the performance of the phase

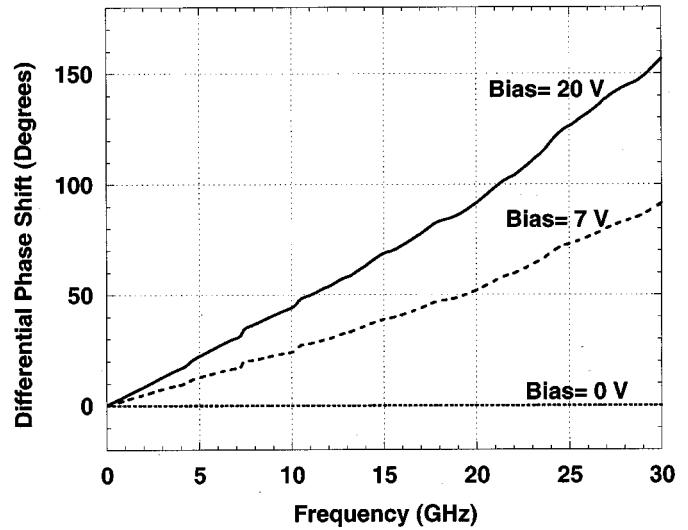


Fig. 2. Differential phase shift versus frequency for selected values of varactor bias. The phase shift is with respect to the transmitted phase at  $0\text{-V}$  bias.

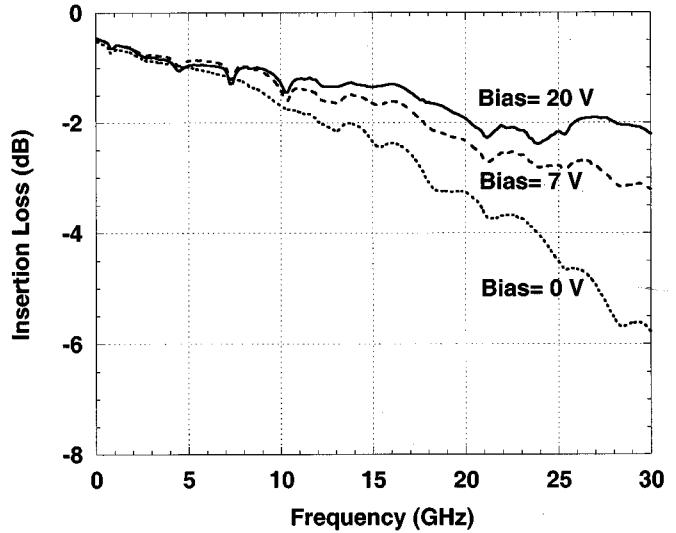


Fig. 3. Insertion loss versus frequency for selected values of varactor bias.

shifter circuits. One-port reflection measurements were made on a HP 8722D network analyzer at various bias values and fitted to an equivalent circuit model. From the equivalent circuit model, it was determined that the capacitance decreased by a factor of 2.2 with an applied bias of  $20\text{ V}$ . It was also found that the tunable BST capacitors had a quality factor of 10 at a frequency of  $30\text{ GHz}$ . Using these values for the BST capacitors, the circuit described in the previous section was simulated on HP EEsof. The simulated phase shift was  $155^\circ$  in good agreement with the measured data. The simulated insertion loss was  $4.8\text{ dB}$ , which is about  $1\text{ dB}$  lower than the measured data. This disparity between the measured and simulated insertion loss results is due to the inability of the simulations to take into account the losses in the silicon substrate. One important observation from the simulations was that the bulk of the phase shifter insertion loss is due to the low quality factor of the BST capacitors. Further improvements in BST capacitor quality

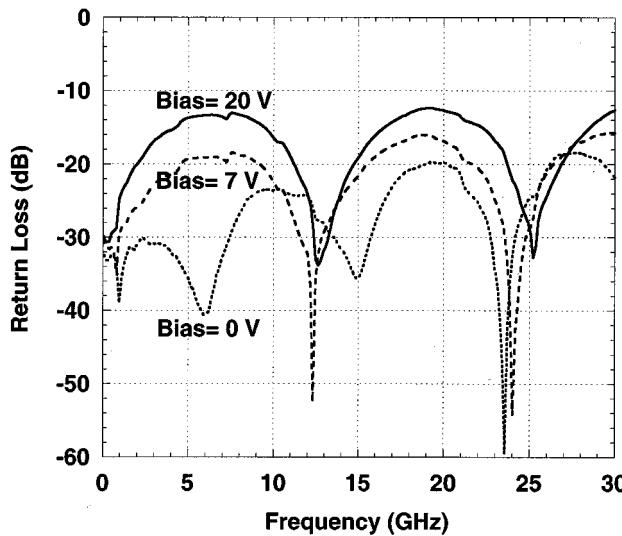


Fig. 4. Return loss versus frequency for selected values of varactor bias.

factors due to advances in BST film processing and growth should lead to phase shifters with even better insertion loss performance.

## II. CONCLUSION

A monolithic *Ka*-band phase shifter that employs voltage tunable BST capacitors has been designed, fabricated, and tested. The phase shifter demonstrated continuous phase shift from 0° to 157° at 30 GHz with control voltages in the range 0–20 V. The maximum insertion loss was 5.8 dB and return loss was better than 12 dB over all phase states. In addition to promising insertion loss performance (27.1°/dB) at 30 GHz, the circuit reported here has several advantages over previously reported BST phase shifters such as moderate control voltages (20 V), room temper-

ature operation, and compatibility with monolithic fabrication techniques.

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