A Wide Bandwidth Monolithic BST Reflection-Type Phase Shifter Using A Coplanar Waveguide Lange Coupler

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Abstract — **A monolithic reflection-type phase shifter fabricated on BST/sapphire is presented here. The phase shifter consists of a coplanar waveguide (CPW) Lange coupler, meandered line inductors, and ferroelectric tunable capacitors. The CPW Lange coupler has a bandwidth of about 52% for 1-dB amplitude balance with center frequency of 2.7 GHz and the isolation is better than 18 dB in the frequency range of 1-3.7 GHz. The phase shifter using the CPW Lange coupler has a phase shift range of more than 90° with an insertion loss of better than 2 dB and a return loss of better than 14 dB in the frequency range of 1.85-2.56 GHz over a bias voltage range from 0 V to 160 V. A figure of merit of 89°/dB at 1.87 GHz and better than 44°/dB from 1.52 to 2.56 GHz was obtained with 160 V. Total size of the monolithic BST phase shifter is 11.2 *mm* × 4.9 *mm* × 0.43 *mm*.**

I. INTRODUCTION

Recently, tunable microwave devices based on ferroelectric materials have been studied for microwave applications such as balanced mixers, amplifiers, phased array antennas, and so on [1]-[5]. By employing ferroelectric materials, the capability of tunable microwave device such as filters, couplers, and phase shifters can be obtained by the variation of the relative dielectric constant ε_r above the Curie temperature using external bias voltage. Among these devices, a continuously variable, or true time delay phase shifter is a critical component of phased array antennas. Compared to conventional tunable phase shifters using varactor diodes, a ferroelectric phase shifter may be realized monolithically by using strontium titanate ($SrTiO_3$) or barium strontium titanate ($Ba_xSr_{1-x}TiO_3$) coated substrates.

A reflection-type phase shifter consists of 3-dB coupler and two identical phase-controllable LC networks, which are connected to the coupled and direct ports of the coupler. The coupler divides the input signal equally between two output ports with a phase difference of 90°. Reflected signals from LC terminations are added at the isolated port of the coupler. This type of phase shifter has good return loss over a large range of phase shift. This paper discusses a design based on the CPW Lange coupler, which has small size and a large bandwidth. The CPW structures are used to confine electric fields near the substrate surface, keeping a large percentage of the electric field in the BST, hence maintaining a high effective dielectric constant and a large tunability. A thick Cr/Cu/Au metalization process, adopted from MEMS techniques, is used to minimize conductor losses in the distributed elements [6]. The metallization for the phase shifter was done using E-beam evaporation. 300 Å of chrome was deposited, followed by 2.7 μm of copper and 0.3 μm of gold to prevent copper from oxidation. Contact exposure and lift-off processes were used to create the metal pattern on the substrate. A 4 μm minimum feature size was patterned on the BST coated substrates. The barium strontium titanate (BST) coated substrates were prepared by MicroCoating Technologies (MCT) using their patented, open-atmosphere combustion chemical vapor deposition (CCVD) process [7]. A composition of $Ba_{0.6}Sr_{0.4}TiO_3$ was used so that the material would be operating in the paraelectric phase and a large change in the relative dielectric constant ε_r with respect to bias voltage would occur. The barium to strontium ratio gives a Curie temperature of −10°C.

II. CIRCUIT DESIGN

The layout and photomicrograph of the CPW Lange coupler are shown in Fig. 1. The design of the Lange coupler starts from the even- and odd- mode characteristic impedance of two coupled lines, as in [8]. The Lange coupler with 3 dB coupling and four interdigital fingers using conductor/BST/sapphire can be realized with line width, $W = 40\ \mu m$, spacing between lines and ground, $S_1 = 300\ \mu m$, spacing between all adjacent lines, $S_2 = 60\ \mu m$, and the length of the coupler, $L = 9400\ \mu m$ according to electromagnetic field simulation using the Microwave Office™. The thicknesses of BST and sapphire substrate are 0.45 μm and 430 μm, respectively.

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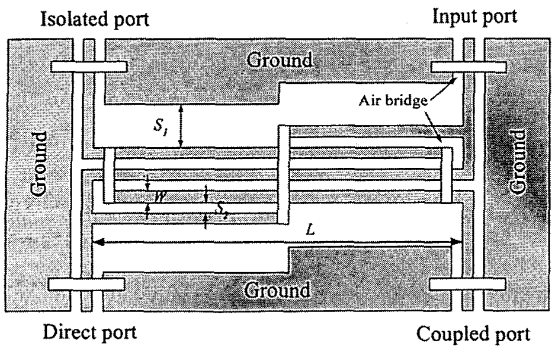
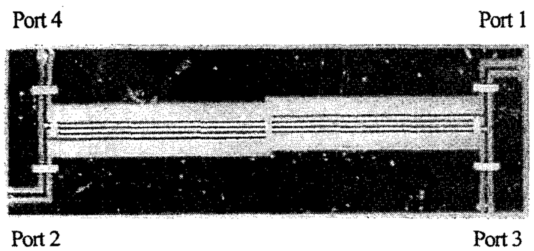


(a)

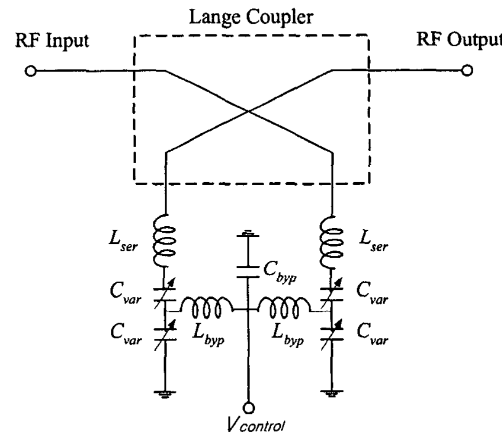


(b)

Fig. 1. (a) Layout of the CPW Lange coupler (W = 40 μm, S_1 = 300 μm, S_2 = 60 μm, L = 9400 μm, and the height of air-bridge = 30 μm) (b) photomicrograph of the fabricated CPW Lange coupler

Air-bridge crossovers are also used to connect ground planes and suppress spurious modes. To minimize coupling, the height of air-bridge is over 30 μm.

Fig. 2 shows the schematic and photomicrograph of the reflection-type phase shifter using the CPW Lange coupler. The 3-dB Lange coupler is combined with two identical LC networks and bias network. The tunable interdigital capacitor, C_{var} has 17 fingers with line width and spacing both equal to 4 μm. The measured capacitance at 2.5 GHz is 4.75 pF with 0 V and 1.7 pF with 80 V. Therefore, tunability (C_{max}/C_{min}) of variable BST capacitor is 2.8 with 80 V. These two tunable interdigital capacitors are placed in series, with the bias voltage applied to the node between them. This allows for the Lange coupler to remain unbiased. Meandered inductors, L_{ser} are placed in series with the tunable capacitors in order to increase the phase shift range. The measured inductance of L_{ser} is about 2.2 nH at 2.5 GHz. The bias isolation network consists of another pair of meandered line inductors, L_{byp} and a bypass capacitor, C_{byp}.



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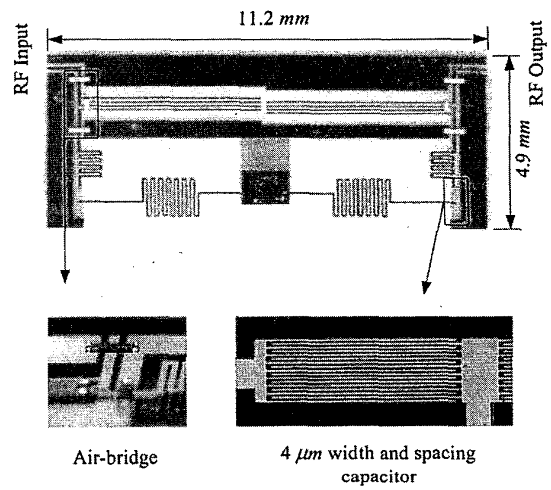

(b)

Fig. 2. (a) Schematic of the reflection-type phase shifter (b) photomicrograph of the reflection-type phase shifter, air-bridge, and 4 μm interdigital capacitor. Total size of the phase shifter is 11.2 $mm \times 4.9$ mm.

III. Experimental Results

S-parameters of the Lange coupler and phase shifter were measured using HP8753C network analyzer and Cascade Microtech ground-signal-ground microwave probes. Network analyzer calibration was done using short-open-load-through (SOLT) calibration standards. S-parameters of the Lange coupler as a function of frequency are shown in Fig. 3. Magnitudes of signals at direct and coupled ports are 3.4 and 3.55 dB at 2.7 GHz, respectively,

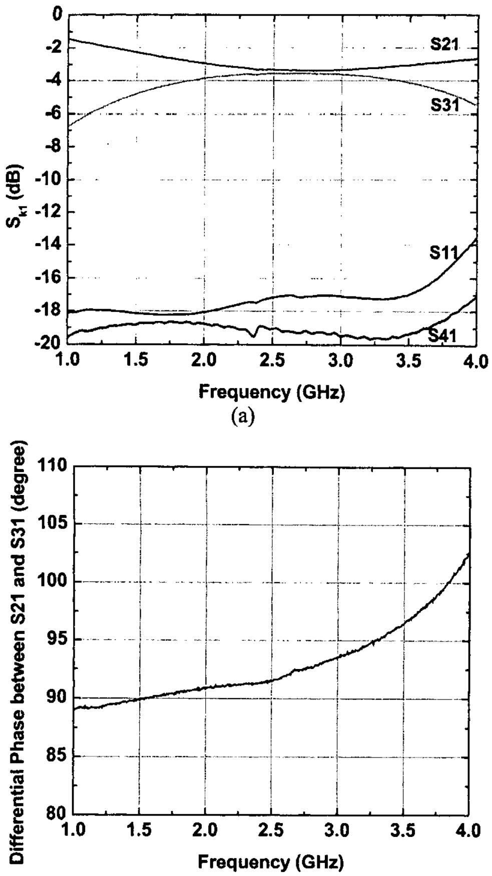

Fig. 3. S-parameter measurement of the CPW Lange coupler. (a) S_{k1} magnitude (b) differential phase shift between direct and coupled ports. The coupler has 3.5 ± 0.5dB in the range of 2-3.4 GHz and phase difference between direct coupled ports is 91.5±2° in the range of 1.3-3 GHz.

as shown in Fig. 3(a). The coupler has 3.5 ± 0.5dB in the range of 2-3.4 GHz, 52% of the center frequency of 2.7 GHz for 1-dB amplitude balance. Also, the isolation is better than 18 dB, and VSWR is better than 1.4 in the same frequency range. A small resonance was observed in the isolation response at 2.35 GHz. We attributed this to waveguide modes propagating beneath the ground plane. Fig. 3(b) shows the differential phase between direct and coupled ports. In the range of 1.3-3 GHz, the differential phase is 91.5°±2°.

The insertion and return loss of the reflection-type phase shifter for bias voltages from 0 V to 160 V with 40 V step in the range of 1-4 GHz, are shown in Fig. 4 and Fig. 5.

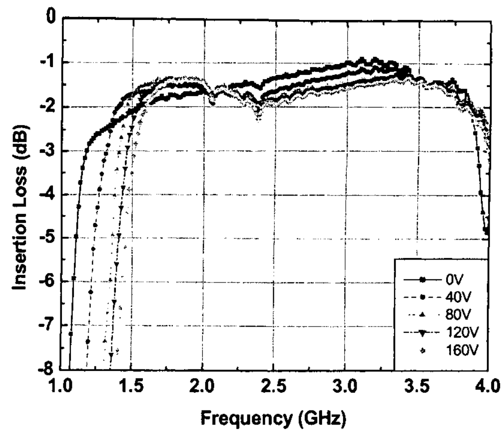

Fig. 4. Insertion loss versus frequency for 0, 40, 80, 120, and 160V in the range of 1-4 GHz.

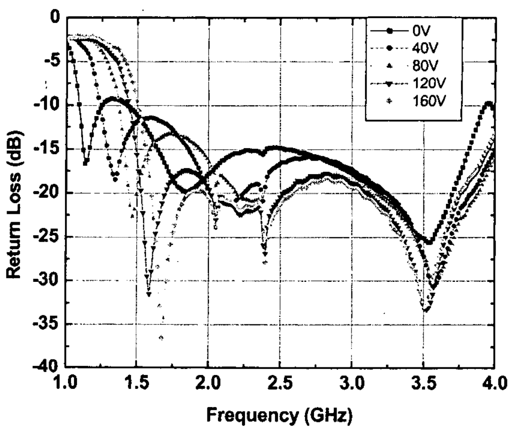

Fig. 5. Return loss versus frequency for 0, 40, 80, 120, and 160V in the range of 1-4 GHz.

Except for the narrow band resonance associated with the Lange coupler isolation response at 2.35 GHz, the maximum insertion loss is 2 dB between 1.6 GHz and 3.7 GHz with all bias states. The insertion loss at 2.43 GHz is about 1.5 dB without bias voltage and increases to about 1.9 dB, achieving an average of 1.7 dB with a bias voltage of 160 V. Also, the return loss is better than 14 dB in the range of 1.85-3.8 GHz. Therefore, from 1.85 to 3.7 GHz, insertion and return loss are better than 2 dB and 14 dB, respectively. Fig. 6 shows the relative phase shift with respect to the phase at 0V for eight different bias levels in the frequency range of 1.4-3 GHz. More than 136° phase shift is achieved at 1.42 GHz and more than 90° between 1.85 and 2.56 GHz with a bias voltage of 160 V. The phase shift is almost linear up to 80V, and begins to saturate above this level.

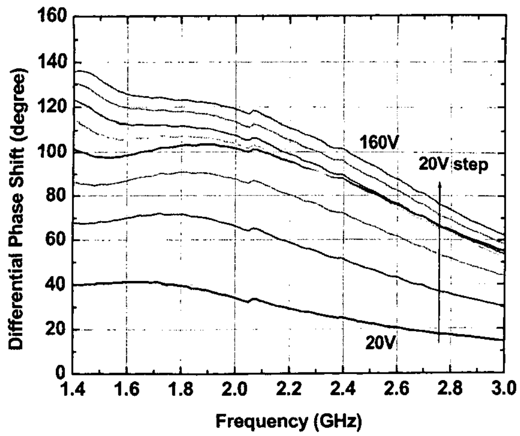

Fig. 6. Differential phase shift versus frequency with respect to phase at 0V for 20 V step.

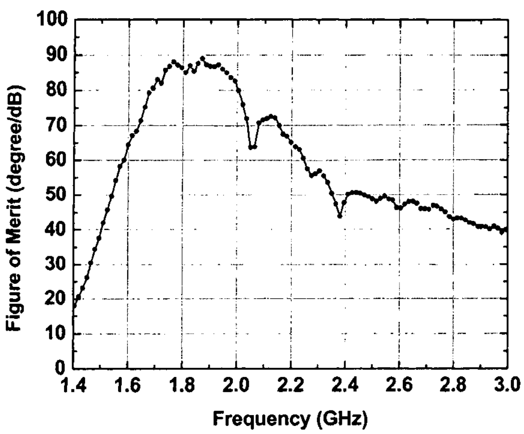

Fig. 7. Figure of merit of differential phase shift per dB of loss versus frequency.

A continuously variable phase shift range of more than 90° with an insertion loss of better than 2 dB and return loss of 14 dB was obtained in the frequency range of 1.85-2.56 GHz with all bias states. The BST reflection type phase shifter presented here has maximum 89°/dB at 1.87 GHz and better than 44°/dB in the range of 1.52-2.56 GHz with a bias voltage of 160 V. Previous researchers have been able to obtain about 100°/dB between 1.8 and 1.9 GHz over bias [3]. However, the total size of the phase shifter reported in [3] would be much larger than that reported in this work. Also, 40°/dB was achieved at 2.43 GHz over the full range of bias [4]. Therefore, the authors believe that this is the best-reported differential phase shift in terms of phase shift per loss, bandwidth, and size for an S-band ferroelectric phase shifter.

IV. Conclusions

A monolithic reflection-type phase shifter using the CPW Lange coupler on $Ba_{0.6}Sr_{0.4}TiO_3$/sapphire was designed, fabricated and tested. Experimental results showed the CPW Lange coupler has 3.5 ± 0.5dB and the isolation of better than 18 dB in the range of 2-3.4 GHz. The measured results of the phase shifter showed over 700 MHz bandwidth centered at 2.2 GHz, with a phase shift of more than 90°, and an insertion loss and a return loss of better than 2 dB and 14 dB, respectively. Also, maximum 89°/dB was achieved at 1.87 GHz with a bias voltage of 160 V. The total size of the phase shifter was less than $11.2\ mm \times 4.9\ mm \times 0.43\ mm$.

Acknowledgement

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