

A Wide-Band Reflection-Type Phase Shifter at S-Band Using BST Coated Substrate

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Abstract—The design and experimental results of a wide-band monolithic reflection-type phase shifter are presented in this paper. The phase shifter fabricated on $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ (BST)/sapphire consists of a coplanar waveguide (CPW) Lange coupler, a series resonated LC termination, and a bias network. The CPW Lange coupler results in a power split of $3.5 \text{ dB} \pm 0.5 \text{ dB}$ in the range of 1.6–3.2 GHz. The BST interdigital capacitor has a tunability (C_{\max}/C_{\min}) of 3.1 with 140 V. Measured and simulated performance of a series resonated LC termination was described. The phase shifter has achieved a phase-shift range of over 90° with an insertion loss of better than 2.0 dB and a return loss of higher than 14 dB in the frequency range of 1.9–2.5 GHz over a bias voltage range from 0 to 160 V. A figure-of-merit of maximum $72^\circ/\text{dB}$ at 2 GHz was obtained. The smaller phase shifter using the folded-type CPW Lange coupler, which maintains a smaller aspect ratio for easier packaging, has an insertion loss of better than 2.3 dB with a phase-shift range of over 130° at 2.5 GHz. Two-tone measurements of the phase shifter indicate an input IP_3 of 32 dBm with 0 V and 41.9 dBm with 60 V. Total size of the monolithic BST phase shifter is $11.2 \text{ mm} \times 4.9 \text{ mm} \times 0.43 \text{ mm}$ for the straight coupler design and $5.4 \text{ mm} \times 6.5 \text{ mm} \times 0.43 \text{ mm}$ for the folded-type design.

Index Terms—Coplanar waveguides (CPWs), ferroelectric capacitors, interdigital capacitors, Lange couplers, phase shifters.

I. INTRODUCTION

RECENTLY, tunable microwave devices based on ferroelectric materials have been studied for microwave applications such as balanced mixers, amplifiers, and phased-array antennas [1]–[8]. By employing ferroelectric materials, the capability of tunable microwave device such as capacitors, filters, couplers, and phase shifters can be obtained by the variation of the relative dielectric constant ϵ_r above the Curie temperature using a dc electric field. Among these devices, a continuously variable phase shifter is the most critical component of phased-array antennas. Compared to analog semiconductor phase shifters, the phase shifter based on ferroelectrics has several advantages such as faster tuning speed, higher power-handling capability, and lower cost [1]–[4].

Phase shifters using strontium titanate (SrTiO_3) or barium strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$) have been developed by several groups. Some groups have investigated a transmission-type phase shifter making use of ferroelectric material, which forms either an entire or a fraction of substrate in order to vary phase velocity controlled by changing capacitance [2]–[5]. Also, the reflection-type phase shifter, which is composed of a rat-race coupler and BST capacitors, has been reported [1]. However, the total size of the phase shifter is too large for compact mobile applications.

In this paper, a small-size reflection-type phase shifter based on $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ is designed and measured. The BST covers the entire microwave substrate, reducing the total size of the circuit. The reflection-type phase shifter consists of a 3-dB coupler, a bias network, and two identical phase-controllable LC terminations, 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 sum at the isolated port of the coupler. If lossless LC terminations are connected to an ideal 3-dB coupler, all the power at input port will emerge from the isolated port. This type of phase shifter has a good return loss over a large range of phase shift. This paper also discusses a coplanar waveguide (CPW) Lange coupler design based on BST, which has 3-dB coupling over a wide bandwidth. Most of the Lange couplers are designed using the microstrip configurations [8]–[11] or a CPW structure based on the multilayer ceramic technology [12], [13]. The main advantages of a CPW Lange coupler over the microstrip couplers are to connect easy shunt devices, to reduce radiation loss, and not to need via-holes [14]. Also, the CPW structure is 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, thus shrinking the size of distributed elements. A thick Cr–Cu–Au metallization process, adopted from microelectromechanical system (MEMS) techniques, is used to minimize conductor losses in the distributed elements [15]. The metallization of the substrate was done using the following process: 200 Å of chrome deposited as an adhesion layer after patterning a thick photoresist layer. On top of the chrome, 2.7 μm of copper was deposited to form the main conductor layer with a cap of 0.3 μm of gold as an oxidation barrier for the copper. A liftoff process was then used to create the metal pattern on the substrate. The BST-coated substrates were prepared by MicroCoating Technologies (MCT), Chamblee, GA, using their open-atmosphere combustion chemical vapor deposition

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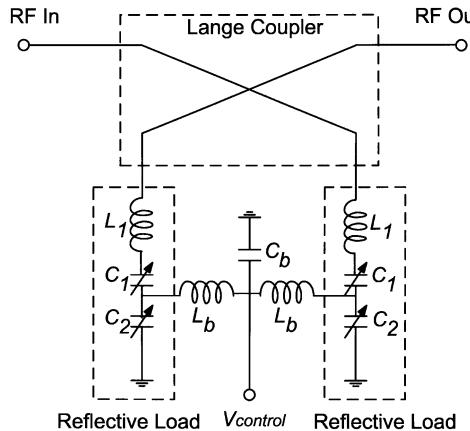


Fig. 1. Schematic of the reflection-type phase shifter.

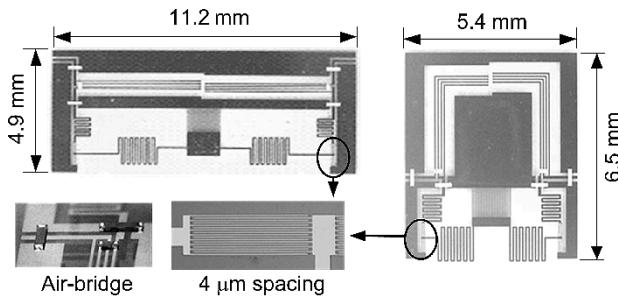


Fig. 2. Photomicrographs of the reflection-type phase shifter using the straight and the folded-type Lange coupler, interdigital capacitor, and air bridge.

(CCVD) process.¹ A composition of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ 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 an expected Curie temperature of -10°C . For this investigation, a single crystal aluminum-oxide substrate was selected resulting in BST with a $\langle 111 \rangle$ orientation. The thicknesses of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ and sapphire are 0.45 and $430\text{ }\mu\text{m}$, respectively.

II. PHASE-SHIFTER DESIGN

The schematic of the designed reflection-type phase shifter is shown in Fig. 1. The CPW Lange coupler with 3-dB coupling and four interdigital fingers based on conductor/BST/sapphire can be realized with a linewidth of $40\text{ }\mu\text{m}$, spacing between the line and ground of $300\text{ }\mu\text{m}$, spacing between all adjacent lines of $50\text{ }\mu\text{m}$, and length of the coupler of $9700\text{ }\mu\text{m}$ using the even- and odd-mode characteristic impedances of two coupled lines [13], [16]. In addition to the straight Lange coupler design, a folded-type Lange coupler was fabricated to reduce the size of the phase shifter and maintain a smaller aspect ratio for easier packaging. Air-bridge crossovers are also used in order to connect alternate fingers and equalize potentials of ground planes and suppress spurious modes. Also, in order to minimize coupling, the height of the air bridge is over $30\text{ }\mu\text{m}$. The photomicrographs of phase shifter, $4\text{ }\mu\text{m}$ interdigital capacitor, and air bridge are shown in Fig. 2.

¹MCT Inc. [Online]. Available: <http://www.microcoating.com>

The reflective termination consists of a series combination of two interdigital capacitors and an inductor in order to increase the phase control range by resonating the capacitive reactance with the inductive reactance. These two capacitors are placed in series with the bias voltage applied to the node between them through the bias network. The differential phase with respect to 0 V is controlled by the variation of capacitance using an external bias voltage. Interdigital capacitors were chosen over parallel-plate capacitors to maintain a planar process that requires no metal layers beneath the BST. If we assume that the value of L_b and C_b are high enough to neglect it, and all parasitics are zero, the voltage reflection coefficient and phase of the LC series termination are expressed by

$$\Gamma = \frac{jX_T - Z_0}{jX_T + Z_0} \quad (1)$$

$$\angle\phi_T = \tan^{-1} \left(\frac{2Z_0X_T}{X_T^2 - Z_0^2} \right) \quad (2)$$

where Z_0 and X_T are the characteristic impedance and total reactance of the LC termination, respectively. The phase variation of the LC series termination is given by

$$\Delta\phi_T = 2 \left[\tan^{-1} \left(\frac{X_{T\max}}{Z_0} \right) - \tan^{-1} \left(\frac{X_{T\min}}{Z_0} \right) \right]. \quad (3)$$

In order to obtain maximum phase shift with a limited tunability of the capacitor, the maximum reactance should be set equal to the minimum reactance with opposite sign ($X_{T\max} = -X_{T\min}$). Therefore, the maximum phase variation and optimal inductance for a lossless LC series termination can be expressed as [17]

$$\begin{aligned} \Delta\phi_T &= 4 \tan^{-1} \left[\frac{C_{1\min} + C_{2\min}}{2\omega Z_0 C_{1\min} C_{2\min}} \left(1 - \frac{1}{r} \right) \right] \\ &= 4 \tan^{-1} \left[\frac{1}{2\omega Z_0 C_{\min}} \left(1 - \frac{1}{r} \right) \right] \end{aligned} \quad (4)$$

$$\begin{aligned} L_1 &= \frac{C_{1\min} + C_{2\min}}{2\omega^2 C_{1\min} C_{2\min}} \left(1 + \frac{1}{r} \right) \\ &= \frac{1}{2\omega^2 C_{\min}} \left(1 + \frac{1}{r} \right) \end{aligned} \quad (5)$$

where r is the ratio of the maximum and minimum capacitance, and C is a series capacitance of C_1 and C_2 . Fig. 3 shows simulated and measured results of two different LC terminations. $LC1$ and $LC2$ have $L_1 = 3.9\text{ nH}$ and 7.5 nH at 2.5 GHz , respectively, with $C_{1\max} = 2.4\text{ pF}$, $C_{2\max} = 3.9\text{ pF}$, and a tunability $r = 3.1$. $LC1$ has a phase shift range of over 155° and a loss of better than 2.2 dB in the frequency range of $2.1\text{--}2.5\text{ GHz}$, whereas $LC2$ has over 200° and better than 2.8 dB between $1.6\text{--}2\text{ GHz}$. To achieve a higher phase shift range, a high inductance and low capacitance are needed according to (4) and (5). However, this can cause a higher loss due to the resistive parasitics. Therefore, a single-series LC termination is suitable for approximately a 180° phase-shift range with a limited tuning range ($r \leq 4$) in terms of loss per decibel.

Generally, 360° phase-shift range is required for a full azimuthal scanning range in an adaptive phased-array antenna system. One way to reach the 360° phase-shift range is using

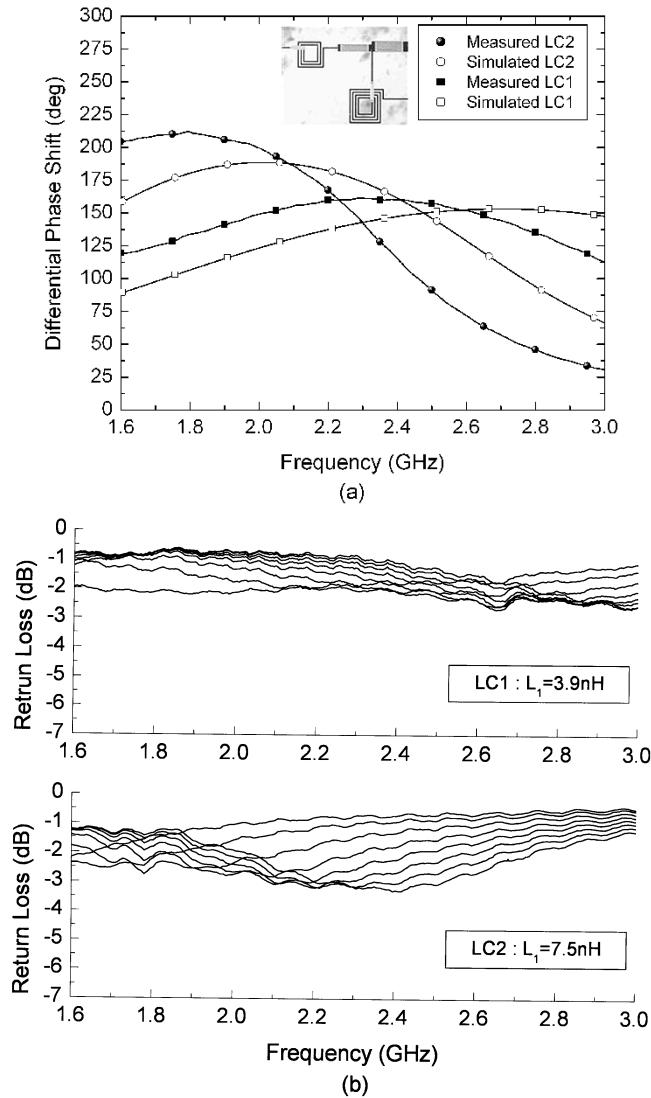


Fig. 3. Simulated and measured performance of two *LC* terminations. (a) Simulated and measured differential phase shift. (b) Measured return loss.

two or more identical stages cascaded [2], [18]. However, the size of this topology for the BST phase shifter herein is too large to enjoy the benefit of the high dielectric material. Another way is that the phase variation of the reflective termination can be increased using two different series resonated terminations, in parallel, as in [19]–[21]. One resonated termination is series resonant at the lowest bias voltage, whereas the other is at the highest voltage. Also, a transformation network is needed in order to reduce a return loss and loss variation.

III. EXPERIMENTAL RESULTS

A. *S*-Parameter Measurement

S-parameter measurements were performed using an HP8753C network analyzer and Cascade Microtech ground–signal–ground microwave probes (150- μm pitch). Network analyzer calibration was done with short-open-load-through (SOLT) using an impedance standard substrate available from Cascade Microtech.² Fig. 4(a)

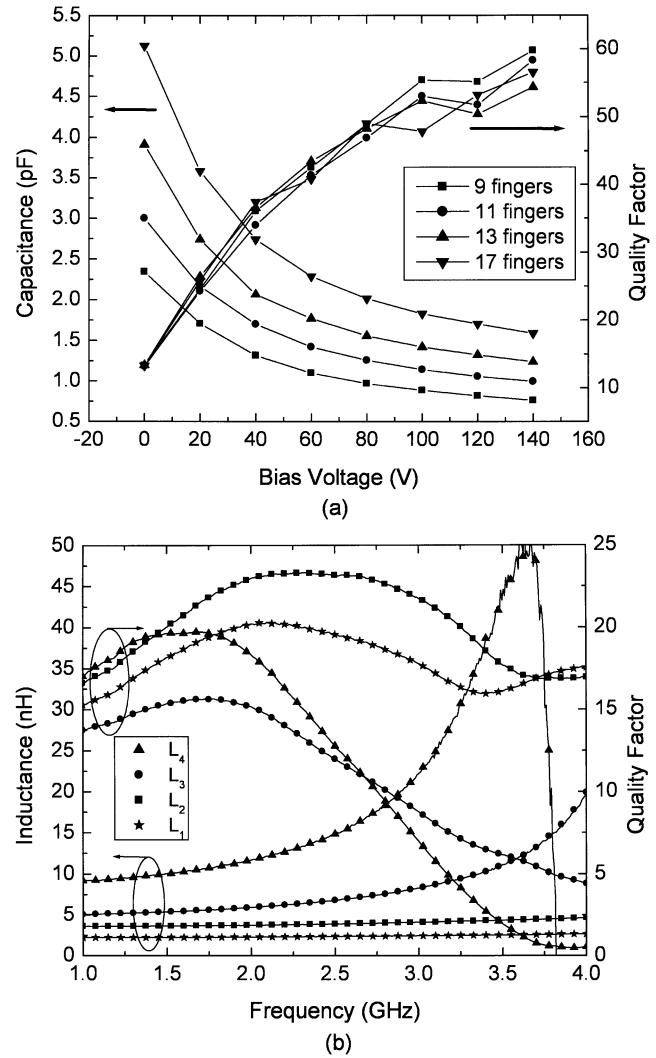


Fig. 4. (a) Bias-voltage dependence of BST capacitance and quality factor of various number of fingers at 2.5 GHz. (b) Inductance and quality factor of spiral inductors (L_2 : 2.75 turn and L_4 : 4.75 turn) and meandered inductors (L_1 : four turn and L_3 : eight turn).

shows the dc-bias voltage dependence of BST interdigital capacitors at 2.5 GHz. As a bias voltage increases, the dielectric constant and loss are reduced. From the measured results, it was determined that the capacitors have a tunability, $\kappa = C(0\text{ V})/C(140\text{ V}) \approx 3.1$ and a maximum quality factor of 60 with a bias voltage of 140 V at 2.5 GHz. In order to achieve a high tunability with a lower bias voltage, spacing of the finger would need to be reduced [5]. However, reducing spacing can cause difficulties in processing the thick metal traces with narrow gaps. Also, intermodulation distortion (IMD) is directly proportional to a tuning voltage for any varactor so that a high tuning voltage can improve nonlinear performance. Such a low-current high-tuning voltage for implementation can be reached using off-the-shelf dc–dc converters designed for LCD backlights.³ Fig. 4(b) shows the variations of inductance and a quality factor as a function of frequency. The meandered inductors have conductor width of 60 μm and spacing between

²Cascade Microtech, Beaverton, OR. [Online]. Available: <http://www.cascademicrotech.com>

³Maxim Integrated Products, Sunnyvale, CA. [Online]. Available: <http://www.maxim-ic.com>

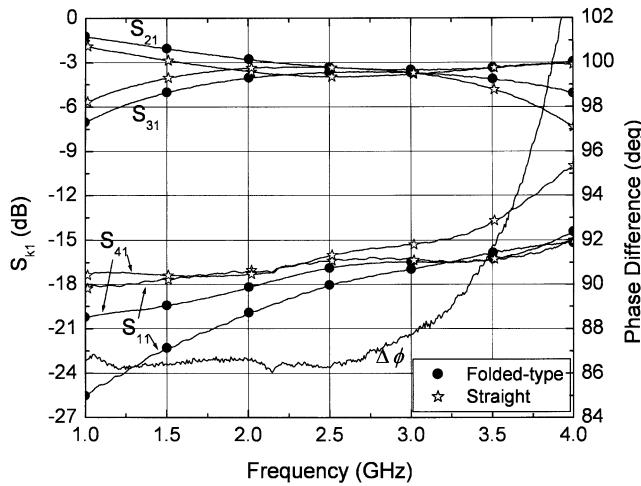


Fig. 5. Measured S -parameters of the CPW Lange couplers.

adjacent lines of $40\ \mu\text{m}$. In addition to the meandered inductors, the spiral inductors were used at the reflective termination in order to obtain a high inductance and small occupied area. The spiral inductors have an inner opening diameter of $180\ \mu\text{m}$, conductor width of $20\ \mu\text{m}$, and conductor interturn space of $20\ \mu\text{m}$. Two meandered inductors, which are used at the phase shifter, have 2.2 and $6.8\ \text{nH}$ with a quality factor of 20 and 12 at $2.5\ \text{GHz}$. Two spiral inductors have 3.9 and $14.9\ \text{nH}$ at $2.5\ \text{GHz}$ with Q of 22.7 and 12.5 depending on the number of turns.

S -parameters of the straight and folded-type CPW Lange couplers as a function of frequency are shown in Fig. 5. Magnitudes of signals at direct and coupled ports are 3.3 and $3.9\ \text{dB}$ at $2.5\ \text{GHz}$, respectively. The coupler has a power split of $3.5\ \text{dB} \pm 0.5\ \text{dB}$ in the range of 1.6 – $3.2\ \text{GHz}$. Also, the isolation is higher than $15\ \text{dB}$, and the return loss is higher than $16\ \text{dB}$ in the same frequency range. The differential phase between the direct and coupled ports is $87^\circ \pm 1^\circ$. The folded-type Lange coupler has a power split of $3.5\ \text{dB} \pm 0.5\ \text{dB}$, with an isolation and a return loss of higher than $16\ \text{dB}$ in the range of 2.15 – $3.4\ \text{GHz}$. Therefore, the CPW Lange couplers on BST show an equal power-splitting performance, good isolation, and return loss over a wide frequency range.

The insertion and return losses of the phase shifter using the straight Lange coupler are shown in Fig. 6. The phase shifters, which are fabricated and tested herein, were designed with a lower inductance ($L_1 = 2.2\ \text{nH}$) than optimal values from (5) using a given capacitance ($C_{1\max} = C_{2\max} = 4.2\ \text{pF}$) in order to reduce the insertion loss of the phase shifter and loss variation.

The insertion loss is less than $2\ \text{dB}$ over most of the frequency range between 1.9 – $3.7\ \text{GHz}$ over all bias states. A narrow-band resonance around $2.35\ \text{GHz}$ increases the insertion loss to a maximum of $2.3\ \text{dB}$. The cause of this resonance is being investigated. The return loss is better than $14\ \text{dB}$ in the same frequency range. Fig. 7 shows the relative phase shift with respect to the phase at $0\ \text{V}$ as a function of frequency for eight different bias levels. Over 90° phase shift is achieved between 1.5 – $2.5\ \text{GHz}$ with a bias voltage of $160\ \text{V}$. Therefore, a continuously variable phase-shift range of over 90° with an insertion loss of better than $2\ \text{dB}$ (not including losses from the resonance

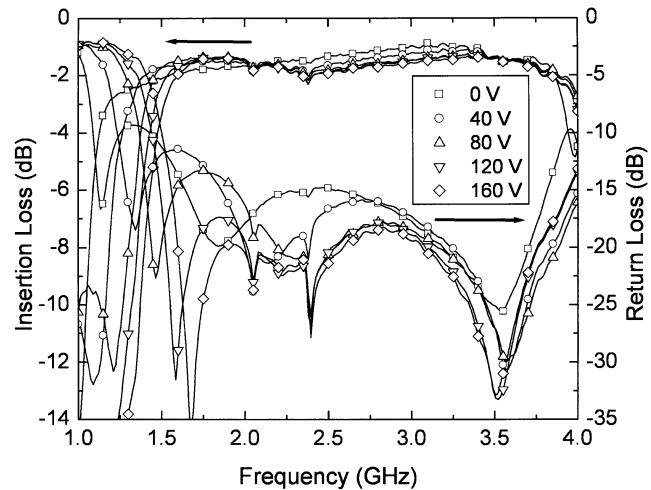


Fig. 6. Insertion and return losses of the phase shifter using the straight Lange coupler for 0 , 40 , 80 , 120 , and $160\ \text{V}$ in the range of 1 – $4\ \text{GHz}$.

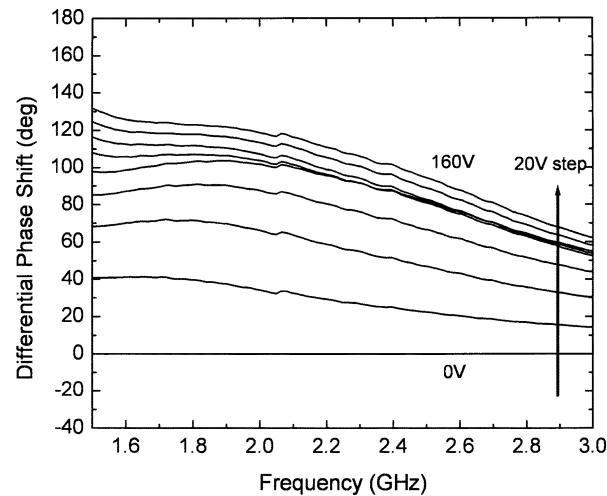


Fig. 7. Differential phase shift using the straight Lange coupler with respect to phase at $0\ \text{V}$ for a 20-V step.

problem) and a return loss of $14\ \text{dB}$ was obtained in the frequency range of 1.9 – $2.5\ \text{GHz}$ with all bias states.

Figs. 8 and 9 show the measured results of the phase shifter using the folded-type Lange coupler. The phase shifter has a phase shift range of 133° with an insertion loss of $2.2\ \text{dB}$, loss variation of $\pm 0.1\ \text{dB}$, and return loss of higher than $19\ \text{dB}$ at $2.5\ \text{GHz}$. Also, a phase-shift range of over 130° was obtained with a bias voltage of $160\ \text{V}$ in the frequency of 2.2 – $2.6\ \text{GHz}$. The overall performance and operating frequency range of this phase shifter are different from the phase shifter using the straight Lange coupler due to slightly different BST properties of both samples such as a dielectric constant or BST thickness.

The figure-of-merit of the phase shifter can be expressed as

$$F = \frac{|\Delta\phi|(\text{deg})}{\alpha_{\max}(\text{dB})} \quad (6)$$

where $\Delta\phi$ and α_{\max} are the differential phase shift and maximum insertion loss, respectively. Maximum $72^\circ/\text{dB}$ at $2\ \text{GHz}$ and $40^\circ/\text{dB}$ in the range of 1.5 – $3\ \text{GHz}$ were achieved with a bias voltage of $160\ \text{V}$ using the straight Lange coupler, as shown in Fig. 10. Also, the phase shifter using the folded-type Lange

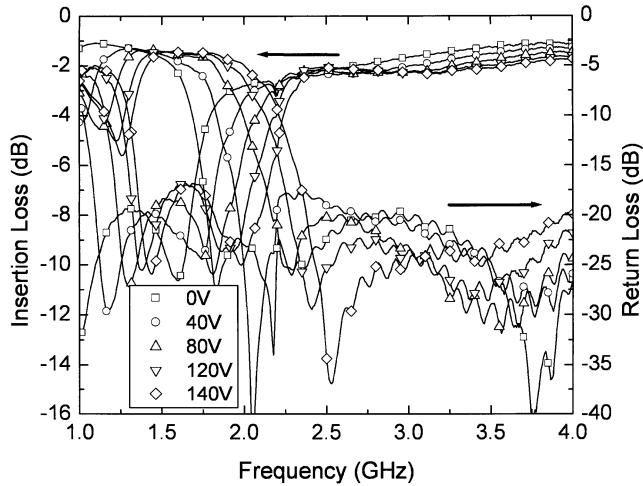


Fig. 8. Insertion and return losses of the phase shifter using the folded-type Lange coupler for 0, 40, 80, 120, and 160 V in the range of 1–4 GHz.

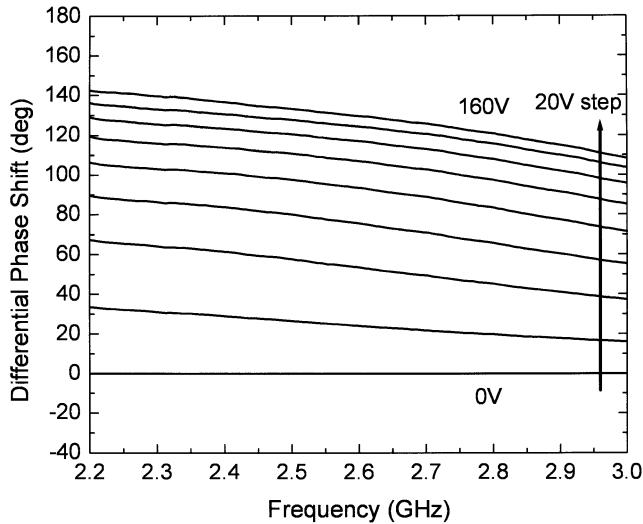


Fig. 9. Differential phase shift using the folded-type Lange coupler with respect to phase at 0 V for a 20-V step.

coupler has maximum $57^\circ/\text{dB}$ at 2.5 GHz. These results compare favorably, in terms of a loss and differential phase shift, to other reported BST phase shifters [1]–[5], and to recently reported GaAs monolithic-microwave integrated-circuit (MMIC) phase shifters [17], [21]. In order to reduce the overall loss of the phase shifter, further improvements in the quality factor of both an inductor and a capacitor should be required by adopting from MEMS techniques [22] and advancement of BST film processing.

B. IMD Measurement

Large-signal characteristics of the phase shifter were performed by two-tone measurement. The equal-power RF signals separated by 500 kHz ($f_1 = 2 \text{ GHz}$ and $f_2 = 2.0005 \text{ GHz}$) are amplified and combined by amplifiers and an in-phase power combiner. A combined output is passed through a low-pass filter in order to reduce the second-order, third-order, and higher order harmonics, and then the signal is applied to the phase shifter. The fundamental and third-order output powers against the input

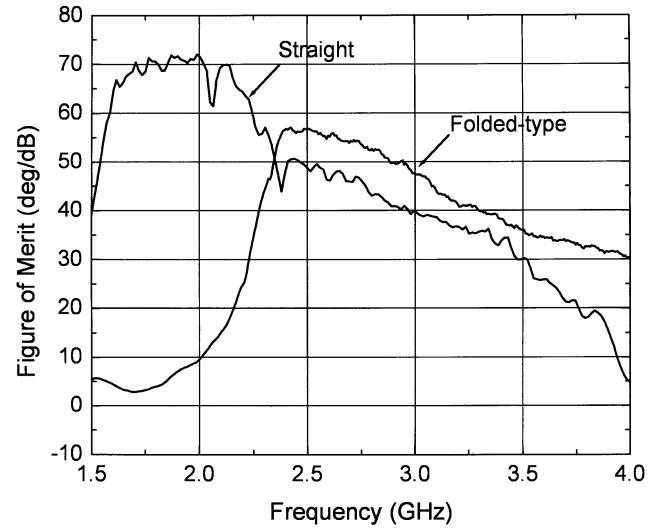


Fig. 10. Figure-of-merit of differential phase shift per decibel of a maximum loss versus frequency.

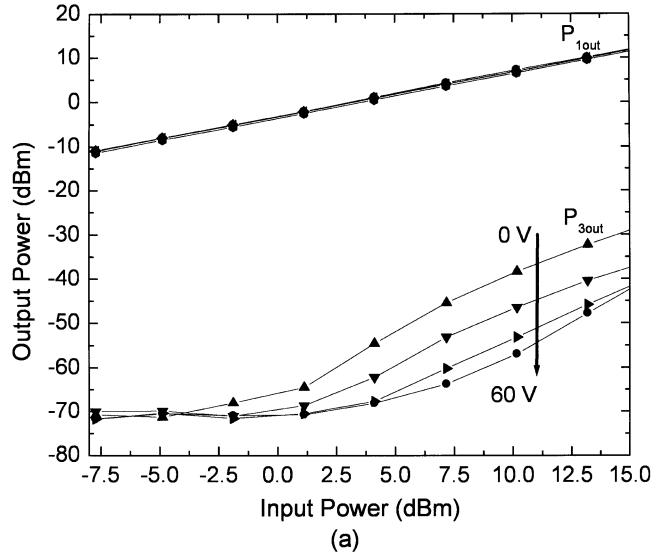


Fig. 11. Nonlinear response of the phase shifter. (a) Output fundamental ($P_{1\text{out}}$) and third-order IMD product ($P_{3\text{out}}$) power versus input power. (b) Input IP_3 versus input power with four different bias voltages.

power were measured for different bias voltages in Fig. 11(a). As a bias voltage increases, third-order output power decreases. Fig. 11(b) shows input IIP_3 (IIP_3) of the phase shifter with different bias voltages. The phase shifter has a worst case IIP_3 of 32 dBm with 0 V and improves to 41.9 dBm at 60 V using an input power range of 2.5–15 dBm. The authors believe this to be the best reported IIP_3 reported to date for any BST phase shifter in this frequency range.

IV. CONCLUSION

We have presented the design and experimental results of a wide-bandwidth monolithic reflection-type phase shifter using the CPW Lange coupler, inductors and high tunable capacitors fabricated on CCVD grown $Ba_{0.6}Sr_{0.4}TiO_3$. The measured results of the phase shifter showed over 600-MHz bandwidth centered at 2.2 GHz, with a phase shift of over 90° , and insertion and return losses of better than 2.0 and 14 dB, respectively. Also, maximum $72^\circ/\text{dB}$ was achieved at 2 GHz with a bias voltage of 160 V. Also, the phase shifter using the folded-type Lange coupler has a good performance. Two-tone IMD measurements were taken over the range bias, indicating a worst case IIP_3 of 32 dBm. The authors believe the reported phase shift per decibel of a maximum loss and IIP_3 to be the best reported to date for any BST phase shifter operating with the 2–4-GHz range with percentage bandwidths of greater than 25%.

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