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

Dongsu Kim, *Student Member, IEEE*, Yoonsu Choi, *Student Member, IEEE*, Mark G. Allen, *Member, IEEE*, J. Stevenson Kenney, *Senior Member, IEEE*, and David Kiesling

***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 $Ba_{0.6}Sr_{0.4}TiO_3$ (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 dB±0.5 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°/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 mm × 4.9 mm × 0.43 mm for the straight coupler design and 5.4 mm × 6.5 mm × 0.43 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 ($Ba_xSr_{1-x}TiO_3$) 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 $Ba_{0.6}Sr_{0.4}TiO_3$ 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

Manuscript received April, 5, 2002.; revised August 26, 2002. This work was supported in part by the Air Force Small Business Innovation Research under Contract F33615-01-M-1950, and by the Yamacraw Design Center, an economic development project funded by the State of Georgia.

D. Kim, Y. Choi, M. G. Allen, and J. S. Kenney are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA.

D. Kiesling is with MicroCoating Technologies Inc., Chamblee, GA 30341 USA.

Digital Object Identifier 10.1109/TMTT.2002.805293

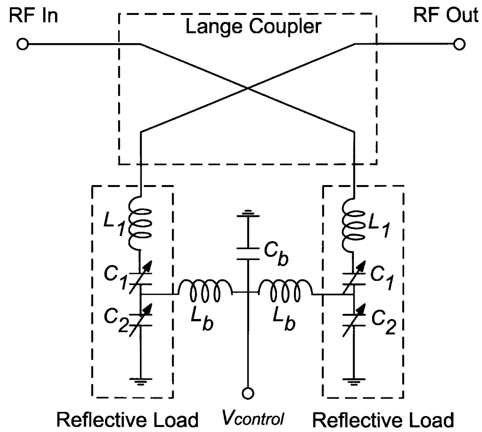


Fig. 1. Schematic of the reflection-type phase shifter.

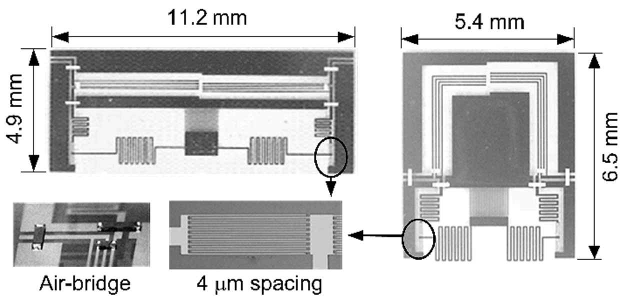


Fig. 2. Photomicrographs of the reflection-type phase shifters using the straight and the folded-type Lange coupler, interdigital capacitor, and air bridge.

(CCVD) process.[1] 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 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 $Ba_{0.6}Sr_{0.4}TiO_3$ and sapphire are 0.45 and 430 μm, 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 μm, spacing between the line and ground of 300 μm, spacing between all adjacent lines of 50 μm, and length of the coupler of 9700 μm 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 μm. The photomicrographs of phase shifters, 4 μm interdigital capacitor, and air bridge are shown in Fig. 2.

[1]MCT 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. Interdigitial 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

$$\Gamma = \frac{jX_T - Z_0}{jX_T + Z_0} \tag{1}$$

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

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

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

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]

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

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

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 $L_1 = 3.9$ nH and 7.5 nH at 2.5 GHz, respectively, with $C_{1\,\max} = 2.4$ pF, $C_{2\,\max} = 3.9$ 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 2.1–2.5 GHz, whereas *LC2* has over 200° and better than 2.8 dB between 1.6–2 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

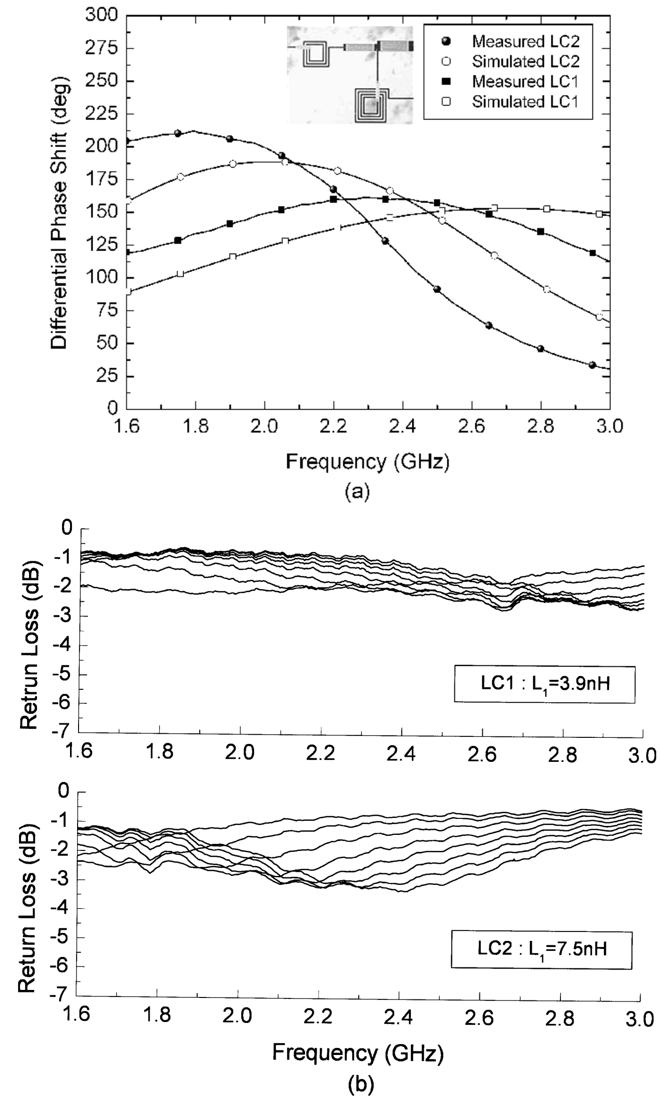


Fig. 3. Simulated and measured performance of two LC terminations. (a) Simulated and measured differential phase shift. (b) Measured return loss.

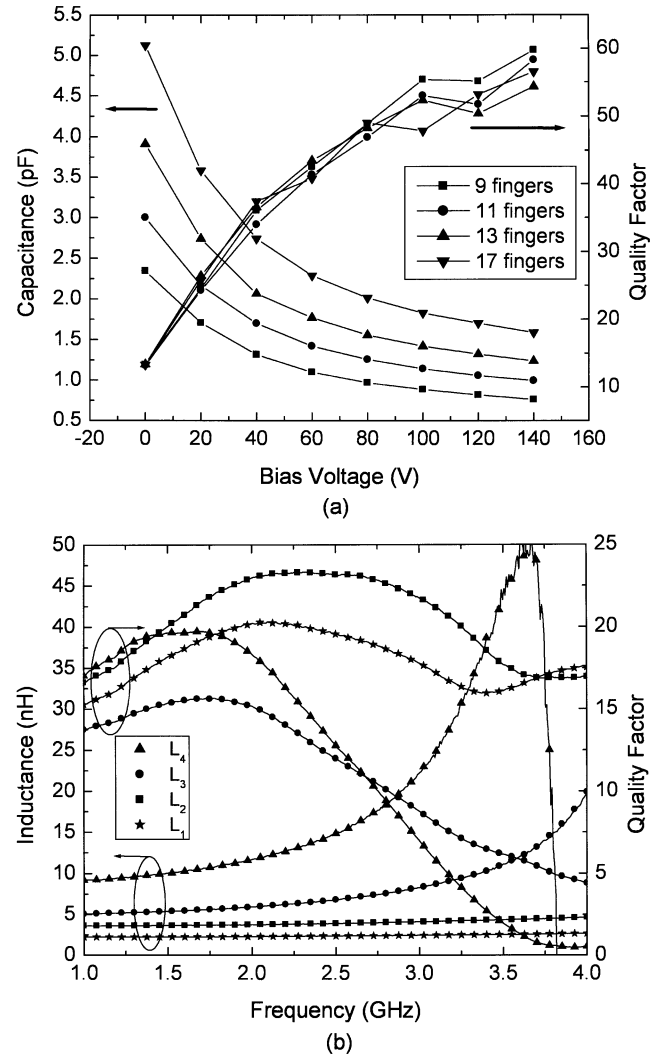


Fig. 4. (a) Bias-voltage dependence of BST capacitance and quality factor of various number of fingers at 2.5 GHz. (b) Inductance and quality factor of spiral inductors (L_2 : 2.75 turn and L_4 : 4.75 turn) and meandered inductors (L_1 : four turn and L_3 : eight turn).

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) 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

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

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

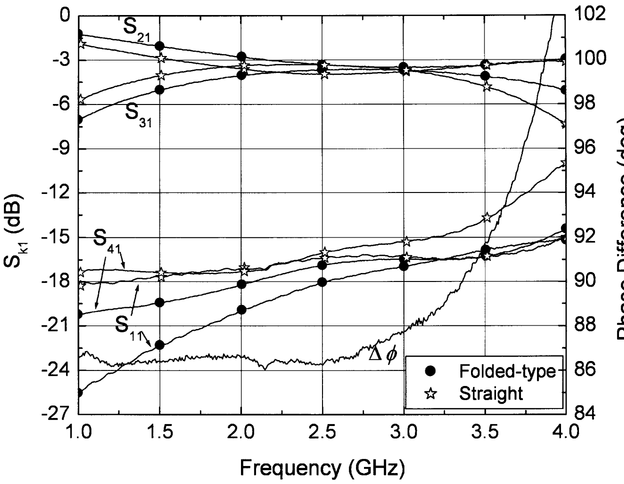


Fig. 5. Measured S-parameters of the CPW Lange couplers.

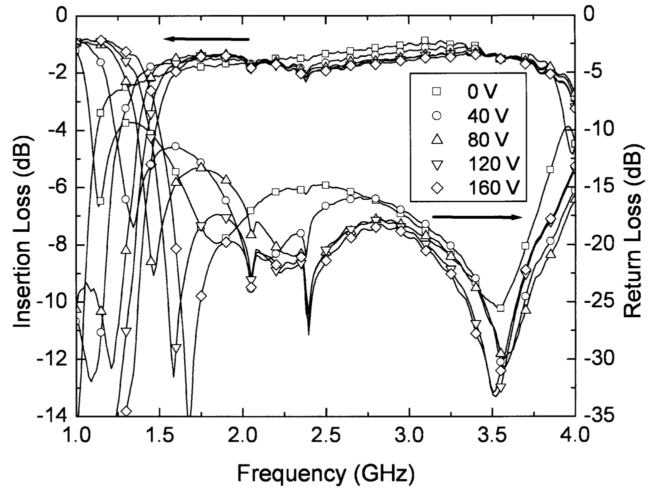


Fig. 6. Insertion and return losses of the phase shifter using the straight Lange coupler for 0, 40, 80, 120, and 160 V in the range of 1–4 GHz.

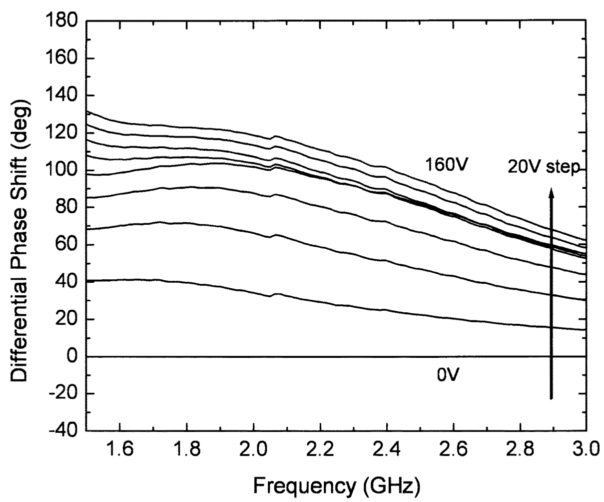


Fig. 7. Differential phase shift using the straight Lange coupler with respect to phase at 0 V for a 20-V step.

adjacent lines of 40 μm. 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 μm, conductor width of 20 μm, and conductor interturn space of 20 μm. Two meandered inductors, which are used at the phase shifter, have 2.2 and 6.8 nH with a quality factor of 20 and 12 at 2.5 GHz. Two spiral inductors have 3.9 and 14.9 nH at 2.5 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 dB at 2.5 GHz, respectively. The coupler has a power split of 3.5 dB$\pm$0.5 dB in the range of 1.6–3.2 GHz. Also, the isolation is higher than 15 dB, and the return loss is higher than 16 dB in the same frequency range. The differential phase between the direct and coupled ports is 87°$\pm$1°. The folded-type Lange coupler has a power split of 3.5 dB$\pm$0.5 dB, with an isolation and a return loss of higher than 16 dB in the range of 2.15–3.4 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 ($L_1 = 2.2$ nH) than optimal values from (5) using a given capacitance ($C_{1\max} = C_{2\max} = 4.2$ pF) in order to reduce the insertion loss of the phase shifter and loss variation.

The insertion loss is less than 2 dB over most of the frequency range between 1.9–3.7 GHz over all bias states. A narrow-band resonance around 2.35 GHz increases the insertion loss to a maximum of 2.3 dB. The cause of this resonance is being investigated. The return loss is better than 14 dB in the same frequency range. Fig. 7 shows the relative phase shift with respect to the phase at 0 V as a function of frequency for eight different bias levels. Over 90° phase shift is achieved between 1.5–2.5 GHz with a bias voltage of 160 V. Therefore, a continuously variable phase-shift range of over 90° with an insertion loss of better than 2 dB (not including losses from the resonance problem) and a return loss of 14 dB was obtained in the frequency range of 1.9–2.5 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 dB, loss variation of $\pm$0.1 dB, and return loss of higher than 19 dB at 2.5 GHz. Also, a phase-shift range of over 130° was obtained with a bias voltage of 160 V in the frequency of 2.2–2.6 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

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

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

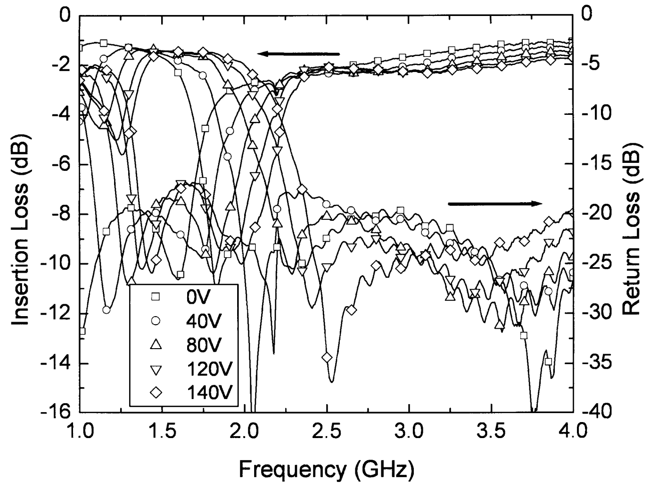


Fig. 8. Insertion and return losses of the phase shifter using the folded-type Lange coupler for 0, 40, 80, 120, and 160 V in the range of 1–4 GHz.

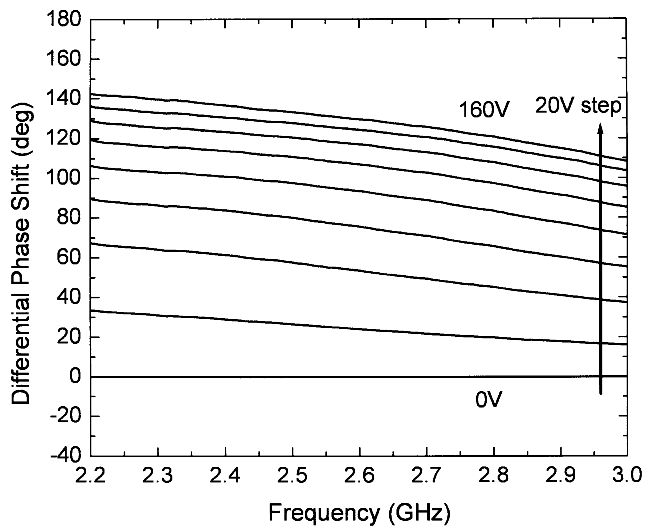


Fig. 9. Differential phase shift using the folded-type Lange coupler with respect to phase at 0 V for a 20-V step.

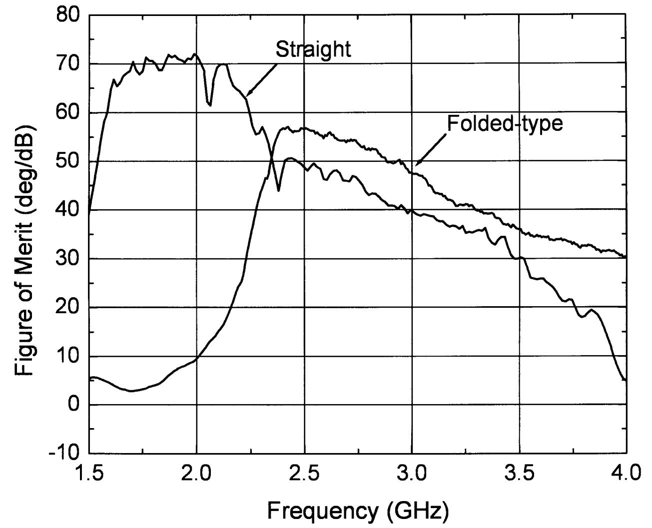


Fig. 10. Figure-of-merit of differential phase shift per decibel of a maximum loss versus frequency.

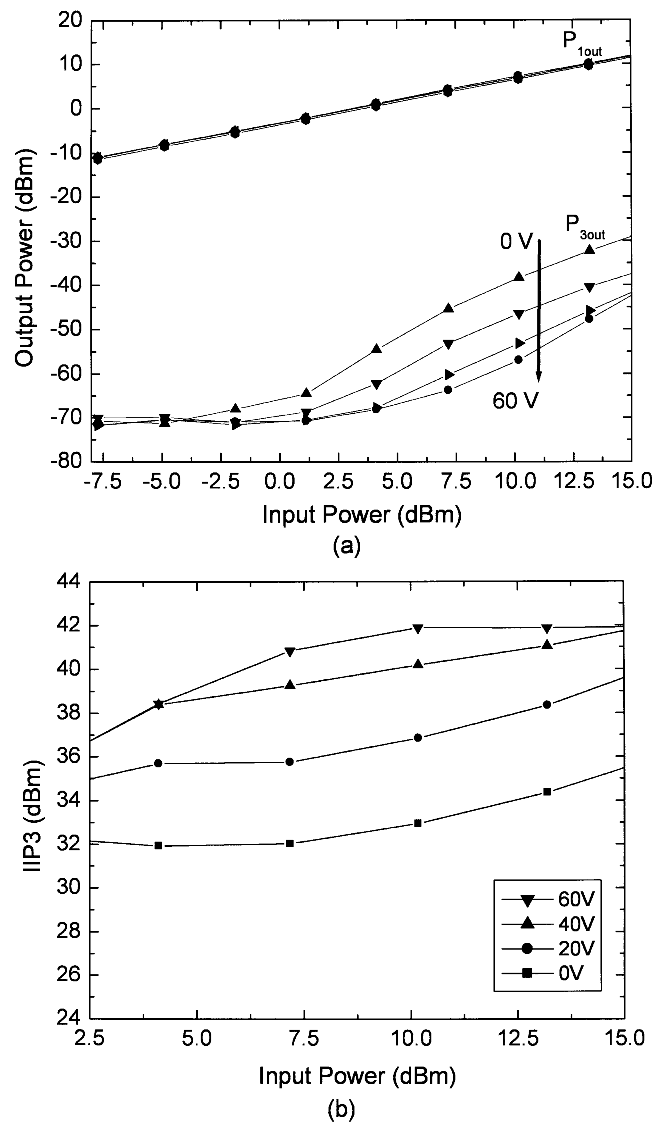


Fig. 11. Nonlinear response of the phase shifter. (a) Output fundamental ($P_{1\mathrm{out}}$) and third-order IMD product ($P_{3\mathrm{out}}$) power versus input power. (b) Input IP_3 versus input power with four different bias voltages.

coupler has maximum 57°/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 ($f_1 = 2$ GHz and $f_2 = 2.0005$ 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 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 IP_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°/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%.

References

[1] A. Kozyrev, A. Ivanov, V. Keis, M. Khazov, V. Osadchy, T. Samoilova, O. Soldatenkov, A. Pavlov, G. Koepf, C. Mueller, D. Galt, and T. Rivkin, "Ferroelectric films: Nonlinear properties and applications in microwave devices," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, 1998, pp. 985–988.

[2] F. De Flaviis, N. G. Alexopoulos, and O. M. Stafsudd, "Planar microwave integrated phase-shifter design with high purity ferroelectric material," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 963–969, June 1997.

[3] A. Kozyrev, V. Osadchy, A. Pavlov, and L. Sengupta, "Application of ferroelectrics in phase shifter design," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2000, pp. 1355–1358.

[4] E. G. Erker, A. S. Nagra, Y. Liu, P. Periaswamy, T. R. Taylor, J. Speck, and R. A. York, "Monolithic Ka-band phase shifter using voltage tunable $BaSrTiO_3$ parallel plate capacitors," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 10–12, Jan. 2000.

[5] Y. Liu, A. S. Nagra, E. G. Erker, P. Periaswamy, T. R. Taylor, J. Speck, and R. A. York, "$BaSrTiO_3$ interdigitated capacitors for distributed phase shifter applications," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 448–450, Nov. 2000.

[6] D. Kim, Y. Choi, M. G. Allen, J. S. Kenney, and D. Kiesling, "A wide bandwidth monolithic BST reflection-type phase shifter using a coplanar waveguide Lange coupler," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2002, pp. 1471–1474.

[7] V. Sherman, K. Astafiev, N. Setter, A. Tagantsev, O. Vendik, I. Vendik, S. Hoffmann, U. Böttger, and R. Waser, "Digital reflection-type phase shifter based on a ferroelectric planar capacitor," *IEEE Microwave Wireless Comp. Lett.*, vol. 11, pp. 407–409, Oct. 2000.

[8] G. Subramanyam, F. A. Miranda, R. R. Romanofsky, F. W. Van Keuls, C. L. Canedy, S. Aggarwal, T. Venkatesan, and R. Ramesh, "A ferroelectric tunable microstrip Lange coupler for K-band applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2000, pp. 1363–1366.

[9] J. Lange, "Interdigitated stripline quadrature hybrid," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 1150–1151, Dec. 1969.

[10] W. P. Ou, "Design equations for an interdigitated directional coupler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 253–255, Feb. 1975.

[11] D. Kajfez, Z. Paunovic, and S. Pavlin, "Simplified design of Lange coupler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 806–808, Oct. 1978.

[12] G. Carchon, W. D. Raedt, and B. Nauwelaers, "Integration of CPW quadrature couplers in multilayer thin-film MCM-D," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 1770–1776, Oct. 2001.

[13] P. Pieters, S. Brebels, E. Beyne, and R. P. Mertens, "Generalized analysis of coupled lines in multilayer microwave MCM-D technology—Application: Integrated coplanar Lange couplers," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1863–1872, Sept. 1999.

[14] R. N. Simons, *Coplanar Waveguide Circuits, Components, and Systems*. New York: Wiley, 2001.

[15] F. Cros and M. G. Allen, "High aspect ratio structures achieved by sacrificial conformal coating," in *Proc. Solid-State Sens. Actuators Conf.*, Hilton Head, SC, 1998, pp. 261–264.

[16] D. M. Pozar, *Microwave Engineering*. New York: Wiley, 1998.

[17] F. Ellinger, R. Vogt, and W. Bächtold, "Compact reflective-type phase-shifter MMIC for C-band using a lumped element coupler," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 913–917, May 2001.

[18] S. Lucyszyn and I. D. Robertson, "Synthesis techniques for high performance octave bandwidth 180° analog phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 731–740, Apr. 1992.

[19] B. T. Henoch and P. Tamm, "A 360° reflection-type diode phase modulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 103–1056, Jan. 1971.

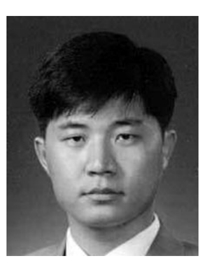
[20] J. P. Starski, "Optimization of the matching network for a hybrid coupler phase shifter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 662–666, Aug. 1977.

[21] F. Ellinger, R. Vogt, and W. Bächtold, "Ultracompact reflective-type phase shifter MMIC at C-band with 360° phase-control range for smart antenna combining," *IEEE Trans. Solid-State Circuits*, vol. 37, pp. 481–486, Apr. 2002.

[22] Y. H. Joung, S. Nuttinck, S. W. Yoon, M. G. Allen, and J. Laskar, "Integrated inductors in the chip-to-board interconnect layer fabricated using solderless electroplating bonding," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2002, pp. 1409–1412.

Dongsu Kim (S'00) was born in Taegu, Korea, in 1972. He received the B.S. degree in electronic and electrical engineering from the Kyungpook National University, Taegu, Korea, in 1997, the M.S. degree in computer and electrical engineering from the Georgia Institute of Technology, Atlanta, in 2001, and is currently working toward the Ph.D. degree in electrical and computer engineering at the Georgia Institute of Technology.

During the summer and the fall of 2001, he was with MicroCoating Technologies, Chamblee, GA, where he was involved with computer simulation and analysis of ferroelectric devices. His research focuses on design and fabrication of microwave circuit, application of ferroelectric materials, and beam-forming network for smart antenna systems.



Yoonsu Choi (S'02) was born in Seoul, Korea, in 1965. He received the B.S. and M.S. degrees in electronics engineering from Soongsil University, Soongsil, Korea, in 1993 and 1995, respectively, and is currently working toward the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta.

From 1995 to 1999, he was with the Korea Telecom Research Center, Seoul, Korea. His current research is RF MEMS and bio-MEMS.

Mark G. Allen (M'89) received the B.A. degree in chemistry, the B.S.E. degree in chemical engineering, and the B.S.E. degree in electrical engineering from the University of Pennsylvania, Philadelphia, in 1984, and the M.S. and Ph.D. degrees from the Massachusetts Institute of Technology (MIT), Cambridge, in 1986 and 1989, respectively.

Since 1989, he has been with the Georgia Institute of Technology, Atlanta, where he is currently a Professor. He was a Visiting Professor with the Swiss Federal Institute of Technology, Zürich, Switzerland, three times over the past 11 years. His research interests are in the areas of micromachining and MEMS, particularly the development and application of new fabrication technologies for micromachined devices and systems. He is the North American Editor of the *Journal of Micromechanics and Microengineering*.

Prof. Allen has served on the Technical Program Committees of three major MEMS conferences and was general co-chair of the 1996 IEEE MEMS Conference. He also serves on the international steering committee for the IEEE MEMS Conference. He was the recipient of the 2000 Research Award of the College of Engineering, Georgia Institute of Technology in recognition of his MEMS research.

J. Stevenson Kenney (S'84–M'85–SM'01) was born in St. Louis, MO, in 1962. He received the B.S.E.E. degree (with honors), M.S.E.E. degree, and Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1985, 1990, and 1994, respectively.

In January 2000, he joined the faculty at the Georgia Institute of Technology, where he is currently an Associate Professor of electrical and computer engineering. He currently teaches and conducts research in the areas of power-amplifier linearization, smart antenna design, and RF integrated circuit (RFIC) design. He possesses over 14 years of industrial experience in wireless communications. He has held engineering and management positions with Electromagnetic Sciences, Scientific Atlanta, and Pacific Monolithics. Prior to rejoining the Georgia Institute of Technology, he was Director of Engineering with the Spectrian Corporation, Sunnyvale, CA. He has authored or coauthored over 40 technical papers, conference papers, and workshop presentations in the areas of acoustics, microelectronics, microwave design, and telecommunications.

Dr. Kenney has been an active member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) for 16 years. He has served as an officer on the Santa Clara Valley chapter of the IEEE MTT-S from 1996 to 2000. He is currently serving his second term on the IEEE MTT-S Administrative Committee (AdCom), and was the treasurer for 2001 and 2002. He served on the IEEE MTT-S International Microwave Symposium (IMS) Steering Committee in 1993 and 1996. He has served on the Editorial Board for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES AND THE IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, and serves on the IEEE MTT-S IMS Technical Program Committee. He is currently co-chair of the RF Components Technical Interest Group of the National Electronics Manufacturing Initiative. He was the Technical Program Committee co-chair for the 2002 Radio and Wireless Conference (RAWCON).

David Kiesling received the Master's degree in mechanical engineering from the Georgia Institute of Technology, Atlanta, and the MBA degree from the Georgia State University, Atlanta.

In September 2000, he joined MicroCoating Technologies Inc., Chamblee, GA, where he is currently a Scientist. He has worked for over seven years in the design and development of antennas, including phased arrays, dipole arrays, and dual reflectors for both commercial and military applications.