A Ku-Band 5-Bit Phase Shifter Using Compensation Resistors for Reducing the Insertion Loss Variation

Woo-Jin Chang and Kyung-Ho Lee

This paper describes the performance of a Ku-band 5-bit monolithic phase shifter with metal semiconductor field effect transistor (MESFET) switches and the implementation of a ceramic packaged phase shifter for phase array antennas. Using compensation resistors reduced the insertion loss variation of the phase shifter. Measurement of the 5-bit phase shifter with a monolithic microwave integrated circuit demonstrated a phase error of less than 7.5° root-mean-square (RMS) and an insertion loss variation of less than 0.9 dB RMS for 13 to 15 GHz. For all 32 states of the developed 5-bit phase shifter, the insertion losses were 8.2 ± 1.4 dB, the input return losses were higher than 7.7 dB, and the output return losses were higher than 6.8 dB for 13 to 15 GHz. The chip size of the 5-bit monolithic phase shifter with a digital circuit for controlling all five bits was 2.35 mm × 1.65 mm. The packaged phase shifter demonstrated a phase error of less than 11.3° RMS, measured insertion losses of 12.2 ± 2.2 dB, and an insertion loss variation of 1.0 dB RMS for 13 to 15 GHz. For all 32 states, the input return losses were higher than 5.0 dB and the output return losses were higher than 6.2 dB for 13 to 15 GHz. The size of the packaged phase shifter was 7.20 mm × 6.20 mm.

I. INTRODUCTION

A phase shifter is a key component for phase-array active antenna systems. Monolithic implementation is advantageous for achieving small size, low cost, and high producibility. Conventional high-pass/low-pass phase shifters use field effect transistor (FET) switching between separate high-pass and low-pass filters [1]-[3]. A phase shifter using high-pass/low-pass filters can be made with a single circuit containing several switching elements. Depending on the states of the switching elements, the phase shifter behaves as either a high-pass or a low-pass filter [4]. To operate a high-pass/low-pass phase shifter, a digital circuit for FET switching is needed. The disadvantage of such phase shifters is that the insertion loss variation for some of the switching elements is too high in a low band operating frequency.

In this paper, we report a Ku-band 5-bit monolithic phase shifter that includes a digital circuit for controlling all five bits. Our phase shifter has two key features: it achieves a low phase error and low insertion loss variation for 13 to 15 GHz.

II. MONOLITHIC PHASE SHIFTER DESIGN FOR LOW INSERTION LOSS VARIATION

The 5-bit phase shifter described in this paper is comprised of 11.25°, 22.5°, 45°, 90°, and 180° phase shifters and was designed with an Agilent Libra simulator. Each of the five bit phase shifters consists of a cascaded series and shunt metal semiconductor field effect transistor (MESFET) switches, metal-insulator-metal capacitors, micro-striplines, and thin film

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Manuscript received Mar. 26, 2002; revised Oct. 1, 2002.

Woo-Jin Chang (phone: +82 42 860 1270, e-mail: wjchang@etri.re.kr) is with Microwave Devices Team, ETRI, Daejeon, Korea.

Kyung-Ho Lee (e-mail: khl259@etri.re.kr) is with Ultra-High Speed Communication IC Team, ETRI, Daejeon, Korea.

resistors. The source and drain of the MESFET are used as the RF terminals, and the gate of the MESFET is used as the switching control terminal. We modeled the switching MESFET as a small series resistor for the on state and as a series capacitor and a large parallel resistor for the off state (Fig. 1). The switching MESFET is in the on state when the gate voltage is + 0.6 V as the forward bias, and in the off state when the gate voltage is – 3.5 V as the pinch-off.

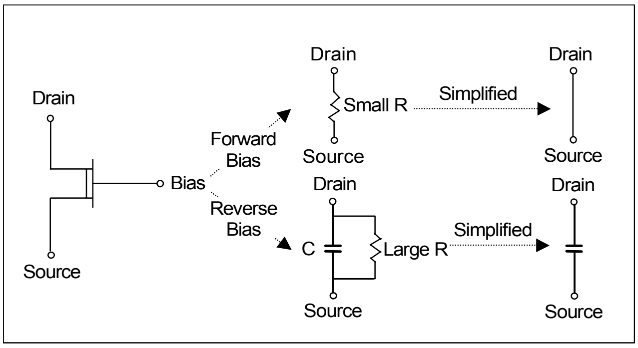

Fig. 1. Switching MESFET model.

We designed the high-pass/low-pass operating phase shifter with several switching MESFETs. Figure 2 depicts a 45° phase shifter using the switching MESFETs. When a switching MESFET had a forward bias, it was modeled as a low resistor. When it had a reverse bias, it was modeled as a capacitor. The equivalent circuits of the 45° phase shifter using switching MESFETs are shown in Fig. 3.

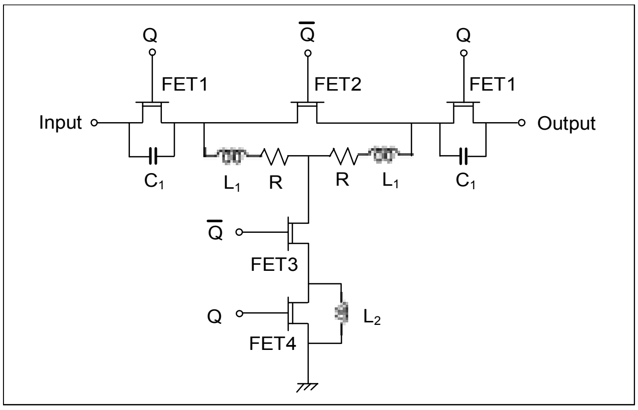

Fig. 2. The schematic of 45° phase shifter.

When the phase shifter without the compensation resistor operates as high-pass and low-pass filters, the relative phase and the insertion losses (ILs) can be expressed as follows:

$$\phi_{relative} = |\phi_{LPF} - \phi_{HPF}|, \tag{1}$$

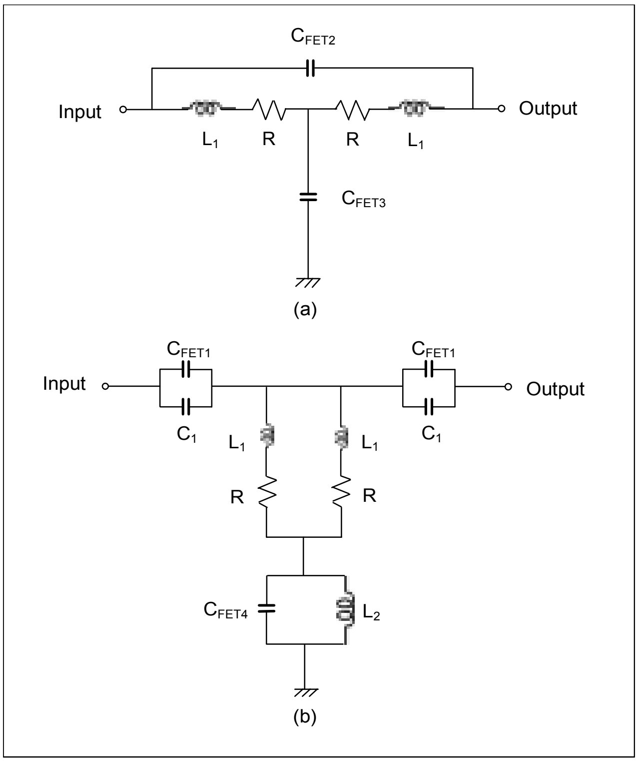

Fig. 3. The equivalent circuits of the 45° phase shifter: (a) for a low-pass filter and (b) for a high-pass filter.

where ϕ represents the phase, subscript *LPF* the low-pass filter, and subscript *HPF* the high-pass filter.

$$IL_{LPF} = |Z_{transfer,LPF}| = 2\omega L_1 C_{FET2}, \tag{2}$$

where $Z_{transfer}$ is the transfer impedance, ω is $2\pi \times$ frequency, and L_1 is the inductance of the micro-stripline.

$$IL_{HPF} = |Z_{transfer,HPF}| = \frac{1}{2\omega C}\left|4 - \frac{1}{\omega^2 C(L_1 + 2L_2)}\right|, \tag{3}$$

where C is $C_1 + C_{FET1}$, C_1 is the capacitance of the MIM capacitor, C_{FET1} is the capacitance of the reverse-biased FET1, and L_2 is the inductance of the micro-stripline.

Eqs. (2) and (3) reveal that the value of the insertion loss for the low-pass filter (IL_{LPF}) is inversely proportional to the value of the insertion loss for the high-pass filter (IL_{HPF}) for frequencies. The compensation resistors as intentional losses (Fig. 3) were inserted between the input and the output of the phase shifter. In the case of the 45° phase shifter without compensation resistors, IL_{LPF} was lower than IL_{HPF}. Thus, when $IL_{LPF} < IL_{HPF}$, the compensation resistors behaved serially between the input and the output of the phase shifter (Fig. 3) only when the phase shifter operated as a low-pass filter. As a result, the compensation resistors reduced the insertion loss variation of the phase shifter.

When the phase shifter with the compensation resistors, as shown in Fig. 3, operates as high-pass and low-pass filters, the relative phase and the insertion losses can be simplified as follows:

$$\phi_{relative,R} = \left|\phi_{LPF,R} - \phi_{HPF,R}\right|, \qquad (4)$$

where subscript R represents the case with the compensation resistors.

$$IL_{LPF,R} = \left|Z_{transfer,LPF,R}\right| = \sqrt{4R^2 + \omega^2(2L_1 - 3R^2C_{FET3})^2}\ , (5)$$

where R is the compensation resistance and C_{FET3} is the capacitance of the reverse-biased FET3.

$$IL_{HPF,R} = \left|Z_{transfer,HPF,R}\right| = \frac{1}{2\omega C}\left|4 - \frac{L_1 + 2L_2}{C(R^2 + \omega^2(L_1 + 2L_2)^2)}\right| .(6)$$

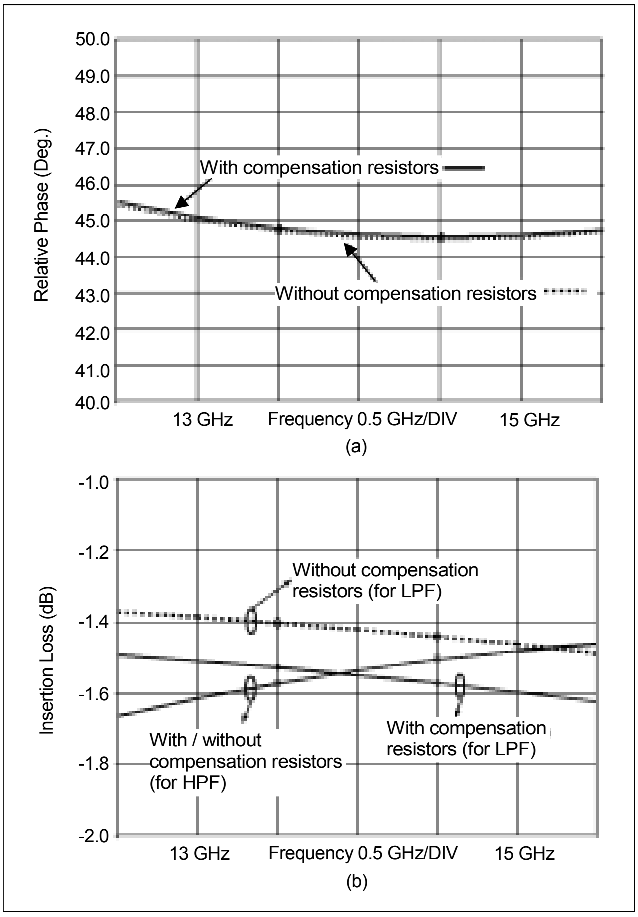

Fig. 4. The relative phases and the insertion losses of the 45° phase shifter with and without compensation resistors: (a) the relative phases and (b) the insertion losses.

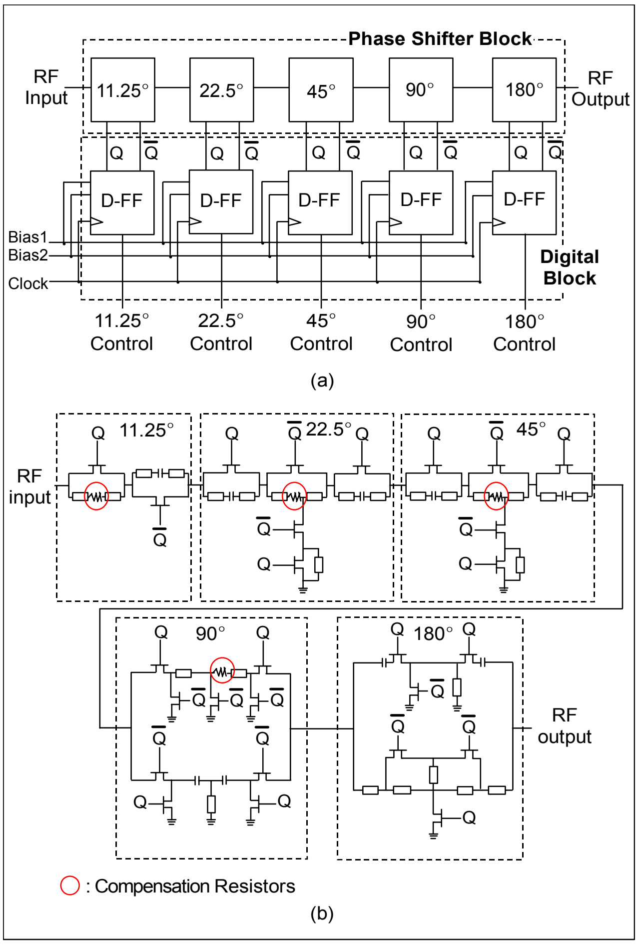

Fig. 5. The 5-bit phase shifter with a digital circuit for controlling all five bits: (a) the block diagram of the 5-bit phase shifter with a digital block and (b) the 5-bit phase shifter circuit.

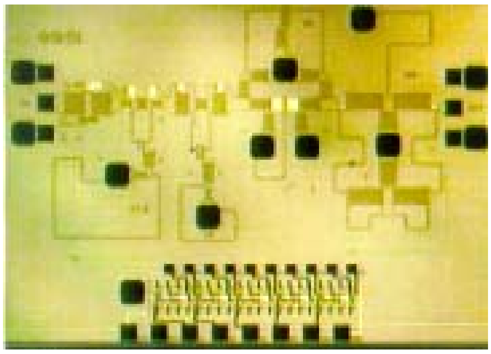

Fig. 6. Microscopic view of the fabricated Ku-band 5-bit monolithic phase shifter.

Comparing (2) with (5), $IL_{LPF,R}$ is higher than IL_{LPF}. The insertion losses of the 45° phase shifters with and without compensation resistors were simulated as shown in Fig. 4. The $IL_{LPF,R}$ of the circuit is higher than the IL_{LPF}, but $IL_{HPF,R}$ is close

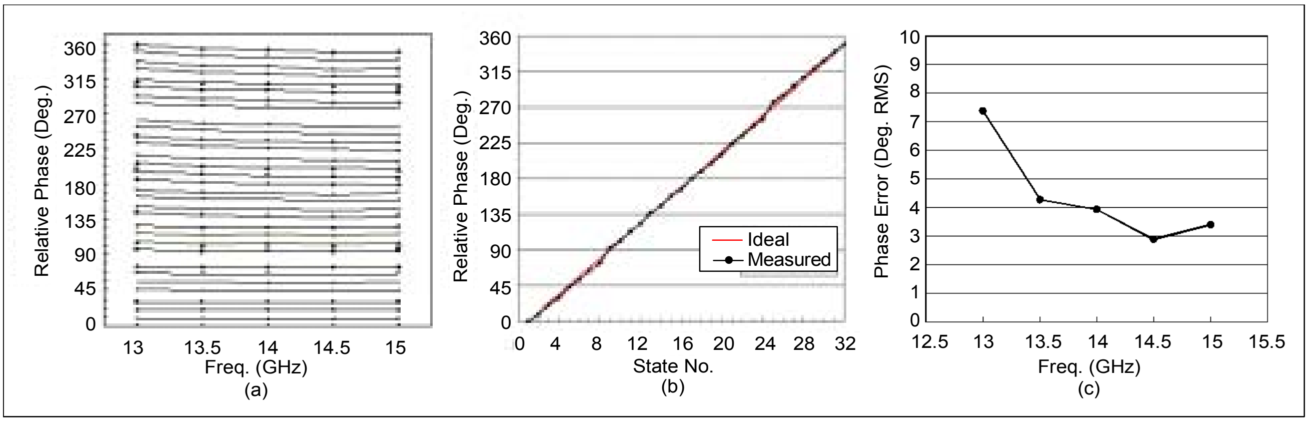

Fig. 7. The measured relative phase characteristics of the 5-bit monolithic phase shifter: (a) the relative phases for all 32states, (b) the measured relative phases compared with the ideal at 14.5 GHz, and (c) the phase errors for 13 to 15 GHz.

to IL_{HPF}. Thus, the insertion loss variation of the 45° phase shifter with compensation resistors is better than that without compensation resistors. Phase shifters with 11.25°, 22.5°, 90° and 180° were designed by the same method to achieve low insertion-loss variations.

Figure 5 gives a block diagram and schematic of the 5-bit phase shifter with a digital circuit for controlling all five bits. The monolithic microwave integrated circuit (MMIC) was fabricated by the TriQuint TQTRX$^{\mathrm{TM}}$ foundry using a 0.6 μm gate length GaAs MESFET process.

Figure 6 is a photograph of the fabricated Ku-band 5-bit phase shifter MMIC. The 11.25°, 22.5°, 45°, 90° and 180° phase shifters are connected in a series. The chip size of the phase shifter including the digital circuit is 2.35 mm×1.65 mm.

III. KU-BAND 5-BIT MONOLITHIC PHASE SHIFTER PERFORMANCE

On-wafer measurements of the fabricated 5-bit monolithic phase shifter were performed with a HP8510C network analyzer for 13 to 15 GHz. Figure 7 shows the measured relative phase characteristics of the 5-bit monolithic phase shifter.

For all 32 states at 14.5GHz, the measured relative phases were in good agreement with the ideal ones as shown in Fig. 7(b). The phase error was less than 7.5° root-mean-square (RMS) for 13 to 15 GHz (Fig. 7(c)). At a frequency of 14.5 GHz, a phase error less than 2.9° RMS was obtained.

The measured insertion loss of the 5-bit monolithic phase shifter is shown in Fig. 8. For 13 to 15 GHz, the insertion losses for all 32 states were 8.2 ± 1.4 dB and the insertion loss variation was less than 0.9 dB RMS. Figure 9 shows the measured input and output return losses of the 5-bit monolithic phase shifter. For all 32 states of the 5-bit phase shifter, the measured input and output return losses were higher than 7.7 dB and 6.8 dB, respectively, for 13 to 15 GHz.

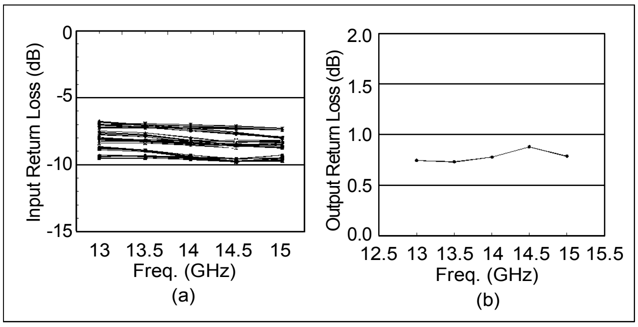

Fig. 8. The measured insertion loss of the 5-bit monolithic phase shifter: (a) the insertion loss for all 32 states and (b) the insertion loss variation for all 32 states.

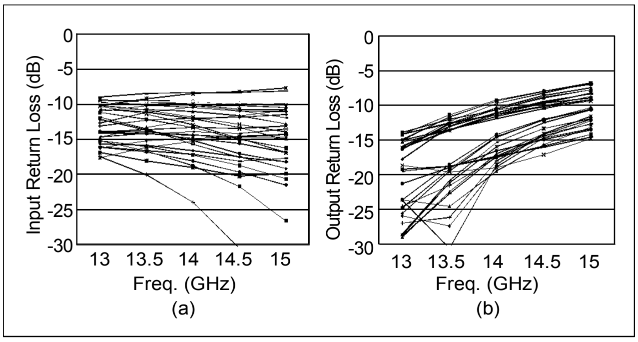

Fig. 9. The measured input and output return losses of the 5-bit monolithic phase shifter: (a) the input return loss for all 32 states and (b) the output return loss for all 32 states.

IV. PACKAGED KU-BAND 5-BIT MONOLITHIC PHASE SHIFTER PERFORMANCE

Figure 10 is a photograph of the packaged Ku-band 5-bit phase shifter. The chip size of the packaged phase shifter is 7.2 mm × 6.2 mm.

The measured relative phase characteristics of the packaged phase shifter are shown in Fig. 11. The phase error was less

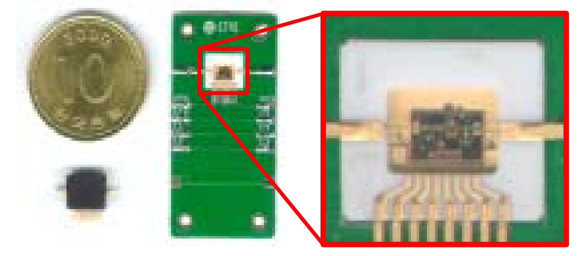

Fig. 10. Photograph of the packaged Ku-band 5-bit monolithic phase shifter.

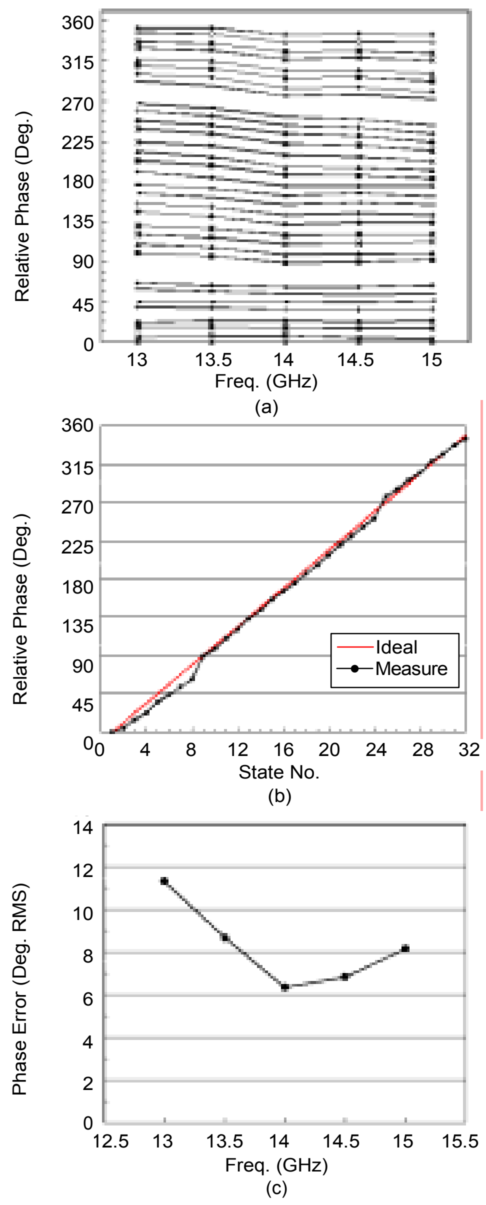

Fig. 11. The measured relative phase characteristics of the packaged phase shifter: (a) the relative phases for all 32 states, (b) the measured relative phases compared with the ideal at 14.5 GHz, and (c) the phase errors for 13 to 15GHz.

than 11.3° RMS for 13 to 15 GHz. At a frequency of 14.5 GHz, a phase error of less than 6.8° RMS was obtained. The measured insertion loss of the packaged phase shifter is shown in Fig. 12. For 13 to 15 GHz, the insertion losses for all 32 states were 12.2 ± 2.2 dB and the insertion loss variation was less than 1.0 dB RMS.

The measured input and output return losses of the packaged phase shifter are shown in Fig. 13. For all 32 states of the 5-bit phase shifter, the measured input and output return losses were higher than 5.0 dB and 6.2 dB, respectively, for 13 to 15 GHz.

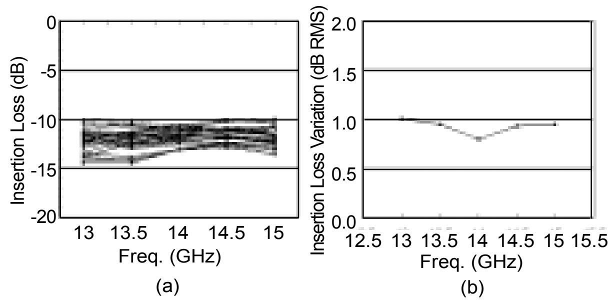

Fig. 12. The measured insertion loss of the packaged phase shifter: (a) the insertion loss for all 32 states and (b) the insertion loss variation for all 32 states.

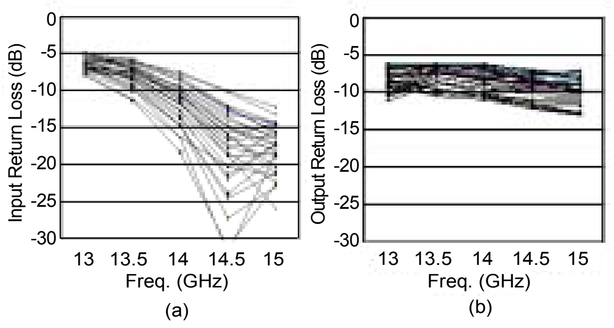

Fig. 13. The measured input and output return losses of the packaged phase shifter: (a) the input return loss for all 32 states and (b) the output return loss for all 32 states.

V. CONCLUSION

We used compensation resistors to reduce the insertion loss variation of a Ku-band 5-bit phase shifter. The fabricated 5-bit monolithic phase shifter demonstrated a phase error of less than 7.5° RMS for 13 to 15 GHz. Insertion losses of 8.2 ± 1.4 dB and an insertion loss variation of less than 0.9 dB RMS were obtained for 13 to 15 GHz. The chip size of the phase shifter that included a digital circuit for controlling all five bits was 2.35 mm × 1.65 mm. The packaged 5-bit monolithic phase shifter showed a phase error of less than 6.8° RMS at a frequency of 14.5 GHz. Insertion losses of 12.2 ± 2.2 dB and an insertion loss variation of less than 1.0 dB RMS were obtained for 13 to 15 GHz. The size of the packaged phase shifter was 7.2 mm × 6.2 mm. The developed 5-bit monolithic phase shifter featuring a small chip size as well as good performance meets the needs for many applications for Ku-band phased-array active antenna systems.

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Woo-Jin Chang received the BS and MS degrees in information engineering from Korea University, Korea, in 1996 and 1998. From 1998 to 1999, he was with LG Precision, where he worked on CDMA power amplifier MMIC design. In the middle of 1999, he joined Electronics and Telecommunications Research Institute (ETRI), Korea, where he has been engaged in research on device modeling and micro-/millimeter-wave MMIC design for active antenna system and wide-band wireless LAN system. Since March 2002, he has been a Senior Research Staff of the Wireless Communication Devices Department of ETRI. His research interests include device modeling, MMIC design, and packaging.

Kyung-Ho Lee received his BS and MS degrees in metallurgical engineering from Seoul National University in Seoul, Korea, in 1980 and 1982. He earned his PhD degree in materials science and engineering from Stanford University in Stanford, USA, in 1989. From 1989 to 1996, he was with Electronics and Telecommunications Research Institute (ETRI), Korea, as a Senior Member of Research Staff, where he has been engaged in research on advanced compound semiconductor device fabrication. From 1996 to 1998, he was with Eaton Semiconductor Korea, where he was the Director of Applications heading troubleshooting and development of Eaton ion implanter-related processes and hardware. Since 1998, he rejoined ETRI as a Principal Member of Research Staff of the Compound Semiconductor Department to manage national research projects on micro-/millimeter-wave MMIC developments for wireless telecommunications systems. He also headed the establishment of the basis of foundry service of ETRI's 4" compound semiconductor fabrication facility. His research interests are the development of advanced compound semiconductor devices and IC fabrication, and their system applications.