High-Performance Q-Band MMIC Phase Shifters Using InGaAs PIN Diodes

Munho Kim · Jung Gil Yang · Kyounghoon Yang

Abstract

This paper presents the design and implementation of Q-band MMIC phase shifters using InGaAs PIN diodes. The topology using a thin-film microstrip line(TFMS) has been proposed to achieve the desired phase-shift as well as good loss characteristics. Five single-bit MMIC phase shifters have been implemented by using a developed BCB(benzocyclobutene)-based multi-layer fabrication technology. The developed phase shifters have less than 3.4 dB of insertion loss and better than 11 dB of input and output return loss in the frequency range of 43 to 47 GHz. To the authors' knowledge, this is the first demonstration of high-performance InGaAs PIN diode-based MMIC phase shifters operating at Q-band frequencies.

Key words : Phase Shifter, TFMS, BCB, InGaAs PIN Diode.

Ⅰ. Introduction

Recently, the interests in phased array antenna systems have extensively increased owing to the applications of satellite communication and military surveillance[1]. In the phased array systems, microwave/millimeter-wave phase shifters are the key components which control the phase of signal to change the direction of the radiated beam. Many of these systems require tens of thousands of phase shifter MMICs. Accordingly, it is essential to obtain high performance with small chip size. For this purpose, research with various materials and device technologies has been conducted over the past few decades[1]~[5]. In GaAs pHEMT technologies, there have been limitations in its commercialization due to high cost[5]. In silicon MOSFET technologies, the continual scaling down of the device geometries enables its operating frequency to reach microwave/millimeter-wave frequency bands. However, the RF performance of the silicon MOSFET has been degraded at higher frequencies over Ka-bands due to its intrinsic parasitic elements[6]. On the other hand, the InGaAs PIN diode based on InP-based material has better RF performances over various FET devices because of its high cutoff frequency[7].

In this work, InGaAs PIN diode-based Q-band MMIC phase shifters are presented by using a BCB-based multilayer fabrication technology. To achieve the desired phase shift and good matching characteristics, the switched thin-film microstrip line topology is used. The fabricated MMIC phase shifters have good phase-shift and loss characteristics with small intrinsic chip size.

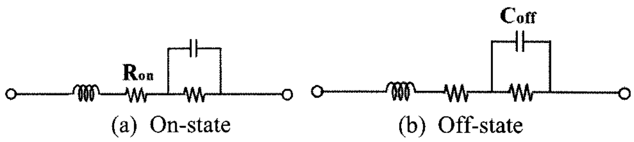

Fig. 1. Equivalent circuit of the fabricated PIN diode.

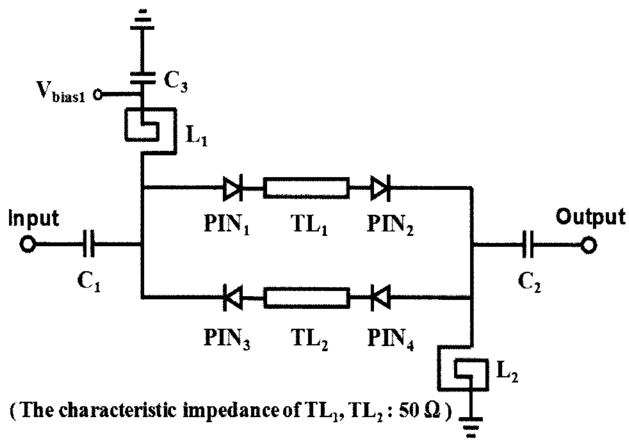

Fig. 2. Circuit configuration of a switched thin-film microstrip line phase shifter.

Table 1. Lengths of the delayed line(TL_1) and the reference line(TL_2).

	TL_2	TL_1 for 11.25°	TL_1 for 22.5°	TL_1 for 45°	TL_1 for 90°	TL_1 for 180°
Length (μm)	260	410	555	830	1,400	2,560

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Ⅱ. Circuit Configuration

Fig. 1 shows on- and off-state equivalent circuits of the fabricated InGaAs PIN diode. If the forward voltage is biased at a PIN diode, it can be regarded as a resistor (on-state resistance). On the other hand, when the PIN diode is biased with the reverse voltage, it functions as the capacitor(off-state capacitance). Required are small on-state resistance(R_{on}) and small off-state capacitance (C_{off}), which are essential for low insertion loss and high isolation, respectively. This InGaAs PIN diode effectively routes RF signals between the delay line(TL_1) and the reference line(TL_2) in the circuit. Fig. 2 shows the circuit configuration of a switched thin-film microstrip line phase shifter proposed in this work. In order to reduce the DC power consumption, the spiral inductors(L_1, L_2) are used in the bias-network. Since impedance of the spiral inductor is very sensitive to the frequency, the value of inductance should be selected by the operating frequency of the circuit. Fig. 3 shows the simplified equivalent circuit of the spiral inductor and the simulation result of the bias-network. Since the parasitic capacitance($C_{parasitic}$) resonates with the main inductance(L_{ind}), the RF signal is reflected the most at the resonance frequency. Accordingly, the leakage of the RF signal through the bias-network can be minimized at the resonance frequency, which is set to be equal to the center frequency of the circuit. Spiral inductors with three different values of inductance(0.67 nH, 1 nH, and 1.8 nH) and the MIM capacitor for the noise immunity in the bias-network are simulated by using the ADS(Advanced Design System) simulation tool. As shown in Fig. 3(c), the inductance of 0.67 nH indicates the best input return loss at the frequency of 45 GHz. Based on this simulation, the spiral inductor with the inductance of 0.67 nH is used in the bias-network. MIM capacitors(C_1, C_2) are used to block the DC current.

The desired phase shift is obtained by utilizing the different phase delays between the delay line(TL_1) and the reference line(TL_2). When the positive voltage is applied at V_{bias}, the PIN diodes(PIN_1, PIN_2) on the delayed line are turned on and the PIN diodes(PIN_3, PIN_4) on the reference line are turned off. Then, the RF signal is transmitted through the delay line. When the negative voltage is applied at V_{bias}, the PIN diodes (PIN_3, PIN_4) on the reference line are turned on and the signal is propagated through the reference line. Based on this circuit operation, the desired phase shift can be achieved. The lengths of the delay line(TL_1) and the reference line(TL_2) are shown in Table 1.

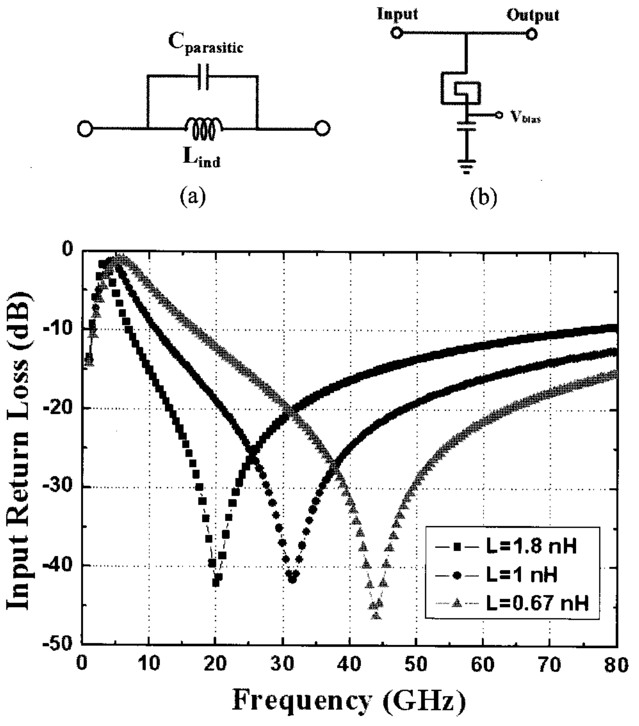

Fig. 3. (a) Simplified equivalent circuit of the spiral inductor, (b) The bias-network, (c) Simulated input return loss of the bias-network.

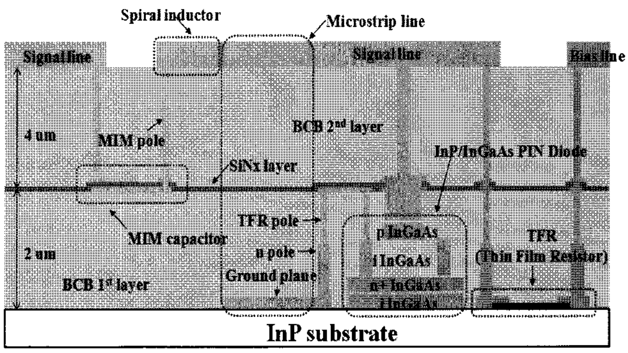

Fig. 4. Cross-sectional view of the fabricated MMIC phase shifter.

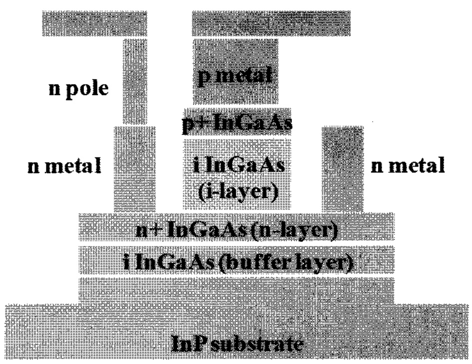

Fig. 5. Cross-sectional view of the fabricated PIN diode.

Table 2. The epi-structure of the fabricated PIN diode.

Layer	Material	Thickness	Doping level
p^+ contact layer	InGaAs	500 Å	8×10^{19}(C)
Intrinsic layer	InGaAs	13,000 Å	5×10^{14}(Si)
n^+ contact layer	InGaAs	7,000 Å	3×10^{19}(Si)
Buffer	InGaAs	1,000 Å	undoped
Substrate	InP	600 Å	undoped

Ⅲ. Fabrication Technology for InGaAs PIN Diodes and Multi-layer Structure

Fig. 4 shows the cross-sectional view of the fabricated MMIC phase shifter composed of InGaAs PIN diodes and various passive elements such as MIM capacitors, spiral inductors, and thin-film microstrip lines. Benzocyclobutene(BCB) is a dielectric material with a low dielectric constant(ε_r=2.65) and a small dielectric loss (0.0008). In addition, it has low viscosity(52 cSt) and low curing temperature(210 ℃). These characteristics make BCB one of the best candidates for the dielectric material. The fabrication sequence of this work is described below. Firstly, InGaAs PIN diodes were fabricated by selective chemical wet-etching and the non-alloyed metallization process. The cross-sectional view of the fabricated PIN diode and its epi-structure are shown in Fig. 5 and Table 2, respectively. The epi-structure is optimized by considering the on-state resistance and the off-state capacitance, which decide the RF performance of the PIN diode. For the p^+ and n^+ contact layer, the highest doping level is applied to achieve a small on-state resistance. The intrinsic layer is doped very low for a small off-state capacitance. The thickness of the intrinsic layer is set to be 1.3 μm for the high switching speed. The fabricated PIN diode with p-metal size of 10×10 μm obtained 1.6 Ω of on-resistance and 20 fF of off-capacitance, resulting in a high cut-off frequency ($f_{cutoff}=1/2\pi \cdot R_{on} \cdot C_{off}$) over 5 THz. The poles which connect the devices between the 1st layer and the 2nd layer were evaporated by using a thermal evaporation process(Ti/Au) for interconnection. The BCB 1st layer was spin-coated, cured, and etched after the bottom ground plane had been formed. The MIM capacitor with a capacitance value of 160 pF/mm^2 was formed between two BCB layers. For the second dielectric layer, BCB was spin-coated, cured, and etched. Finally, the top signal line for the microstrip line and the spiral inductor was formed with a thickness of 2 μm. The TFMS was comprised of the bottom metal ground plane, 6 μm- thick dielectric layers including the BCB multi-layers, and the 2 μm-thick top signal line. The width(16 μm) and the distance(6 μm) between the ground and the signal line were decided for the characteristic impedance of 50 Ω. The measured line loss of the fabricated microstrip line was 0.6 dB/mm at 50 GHz. In addition, the chip size is effectively minimized by using a multi-layer fabrication technology and a meandered TFMS.

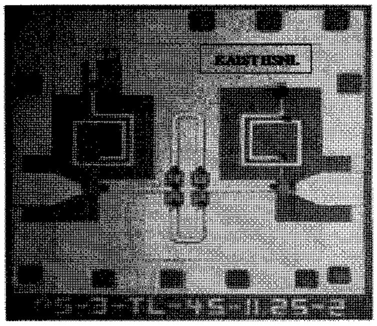

Fig. 6. Microphotograph of the fabricated 11.25° single-bit phase shifter.

Ⅳ. Measurement Results

Five single-bit(180°, 90°, 45°, 22.5°, and 11.25°) MMIC phase shifters have been fabricated. Fig. 6 shows the microphotograph of the fabricated InGaAs PIN diode-based 11.25° single-bit phase shifter. Three MIM capacitors(C_1, C_2, and C_3), four PIN diodes(PIN_1, PIN_2, PIN_3, and PIN_4), two spiral inductors(L_1 and L_2), and two microstrip lines(TL_1 and TL_2) are placed in the circuit as described in Fig. 2.

On a wafer, s-parameter measurements were carried out by using an Anritsu ME7808A network analyzer and a Cascade Microtech probe station. Fig. 7 shows the

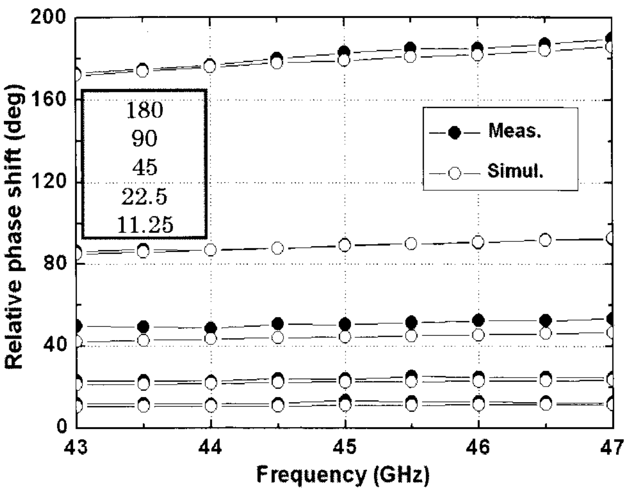

Fig. 7. Measured and simulated relative phase shift of the fabricated five MMIC single-bit phase shifters.

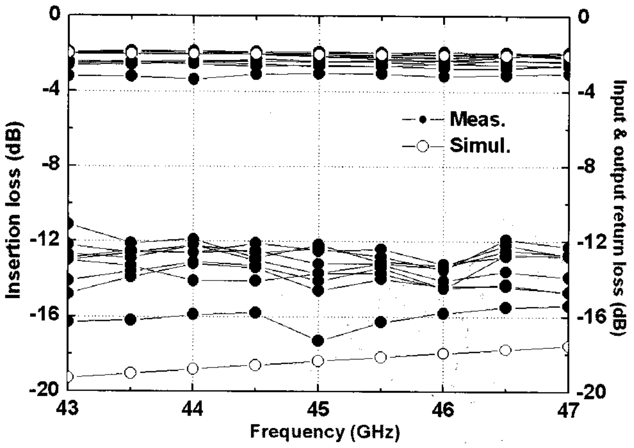

Fig. 8. Measured and simulated insertion loss and return loss of the fabricated five MMIC single-bit phase shifters.

measured relative phase shift of the fabricated MMIC phase shifters.

As shown in Fig. 7, smaller than 10° of phase error was measured at the frequency range of 43 to 47 GHz. The simulated and measured results of the phase shift are in good agreement over the same frequency range. Fig. 8 shows the measured insertion loss and input and output return loss of the fabricated MMIC phase shifters. Less than 3.4 dB of the insertion loss and better than 11 dB of the input and output return loss were measured. The measured and simulated results of loss characteristics are also in good agreement. The overall measurement results are summarized in Table 3. Table 4 shows the performance comparison of the fabricated phase shifter in this work with the other reported Ka- and Q-band MMIC phase shifters. Since the compared MMIC phase shifters are the multi-bit phase shifters, the insertion loss and the chip size are divided by their bits for fair comparisons. The insertion loss per bit obtained from this work is 2.7 dB/bit, which is smaller or comparable to those of the other results as compared in Table 4. In addition, the size per bit is also found to be reduced.

Table 3. RF performance of the five single-bit phase shifters.

Target phase(°)	11.25	22.5	45	90	180
Measured phase(@45 GHz)	13.1	23.9	50.4	89.4	182.6
IL(dB)	<2.4	<2.2	<2.7	<3.4	<2.8
Input RL(dB)	>12.5	>12.2	>11.9	>11.1	>12.1
Chip size(mm^2)	0.86× 0.86		0.92× 0.86	0.97× 0.85	1.05× 0.95

Table 4. Performance comparison of the fabricated phase shifter with the previously published Ka- and Q-band phase shifters.

Ref.	Device technology	Freq. range (GHz)	IL/bit (dB/bit)	Chip size/ bit(mm^2/bit)
[4]	GaAs FET	33~35	3.6	1.25
[8]	GaAs PIN diode	33~35	3	-
[9]	GaAs pHEMT	43~45	2.5	1.87
This work	InGaAs PIN diode	43~47	2.7	0.73

V. Conclusion

InGaAs PIN diode-based MMIC phase shifters have been designed and fabricated by using the BCB-based multi-layer technology. All of the 180°, 90°, 45°, 22.5°, and 11.25° single-bit phase shifters were measured in the frequency range of 43 to 47 GHz. The measurement results show good agreement with simulation. Multi-bit phase shifters can be implemented by cascading the developed single-bit phase shifters.

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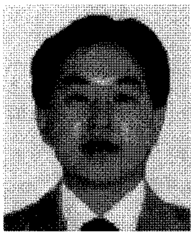

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