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# L-Band SiGe HBT Reflection Type Phase Shifters Using Active Loads with Varactor-Loaded LC-Resonators and RC-Feedback Circuits

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## Abstract

A new reflection-type phase shifter using active loads has been developed for realizing a wide phase-shifting range and small amplitude variations. The active load is based on a common-emitter configuration of HBTs employing varactor-loaded LC-resonators in the load circuit and parallel RC circuits in the series feedback circuit. The varactor-loaded LC-resonator provides a wide phase-shifting range. Meanwhile, the RC-feedback circuit produces negative impedances and improves insertion losses. The implemented reflection-type phase shifter using Si varactor diodes with a capacitance ratio of 2.5:1 and SiGe HBTs with an $f_t$ of 25GHz has achieved a maximal relative phase shift of $290^{o}$. An insertion loss variation was less than 3.2dB and return losses were better than 5.4dB at 1GHz.

**Keywords**: phase shifter, reflection type, active load, SiGe HBT, varactor diode, LC-resonator, feedback circuit, microwave

## 1 Introduction

Recently, the active phased array antennas (APAAs) with beam-forming networks have been actively researched and developed by several companies in the world for the next generation wireless radios, microwave sensors and radars [1]. Accurate phase steering of multiple beams is important for realizing high efficient power combining and tracking [2]-[4]. Nowadays, a variety of reflection type phase shifters have been reported for use in the analog phase modulation and beam forming of the APAA because of bi-directional phase shifting, simple circuitry, zero DC power consumption and wide bandwidth [5]. Most of the reflection type phase shifters have focused on maximizing a phase-shifting range by using multiple varactor diodes or FETs as a load circuit. To achieve a wide capacitance ratio, multiple varactor diodes are combined in parallel or series [6], [7] using lumped or distributed transformers [8], [9]. Meanwhile, multiple varactor-loaded series or parallel LC-resonators are switched on or off [10], [11]. However, little attentions are paid to minimizing insertion losses or insertion loss variations in these papers. The reference [12] has targeted minimal insertion loss variation by employing transformer-based quadrature couplers. The insertion loss was 12.5dB at 24GHz. To address these problems, an enhanced reflection type phase shifter is proposed to minimize insertion losses and insertion loss variations as well as to maximize a phase-shifting range [13]. Contrary to the traditional reflective load using passive circuits with varactor diodes or FETs, the active load with common-emitter transistors in addition to varactor diodes are utilized. The active load employs varactor-loaded LC-resonators in the load circuit for providing a wide phase-shifting range. The LC-resonator, however, sometimes increases insertion losses or insertion loss variations due to the parasitic resistance. To overcome this problem, the active load employs parallel RC circuits in the series feedback circuit. The RC-feedback circuit produces negative impedances and thus improves insertion losses and insertion loss variations. In order to ensure the usefulness of the active load proposed in this paper, the reflection type phase shifters with three different types of loads have been actually designed, fabricated and tested. They are (a) single varactor diode, (b) varactor-loaded LC-resonator, and (c) the active load.

## 2 Circuit Design of the Reflection Type Phase Shifter Using Active Load

### 2.1 Circuit Design of the Reflective Load

A schematic of the reflection type phase shifter is shown in Fig. 1. It is comprised of the 3-dB $90^{o}$ hybrid and the reflective loads. To increase the maximal relative phase-shifting range for a given varactor diode with a limited capacitance ratio, increasing a bandwidth of 3-dB $90^{o}$ hybrid is crucial. Thus two pi-sections of $45^{o}$ LPFs are cascaded instead of the conventional $90^{o}$ LPFs [14]. As a reflective load, three different types shown in Fig. 2 are employed. The reflective load of Fig. 2(a) consists of a single varactor diode $C_V$ and a decoupling capacitor $C_C$. A control voltage $V_C$ is supplied to the varactor diode through a bias resistor $R_V$. The reflective load of Fig. 2(b) employs a varactor-loaded LC-resonator to achieve a wide phase-shifting performance [6], [7]. A parallel LC circuit comprised of $L_1$ and $C_1$ is connected to the reflective load of Fig. 2(a). The reflective load of Fig. 2(c) incorporates an active load to minimize insertion losses and insertion loss variations [13]. It utilizes a common-emitter configuration of HBTs employing the varactor-loaded LC-resonator of Fig. 2(b) in the load circuit to provide a wide phase-shifting range. In addition, parallel RC circuits comprised of $R_E$ and $C_E$ are employed in the series feedback circuit to generate negative impedances and thus minimize insertion losses and insertion loss variations. $V_{CC}$ is a supply voltage. $R_{B1}$ and $R_{B2}$ is a bias resistor for the base bias voltage. $L_B$ and $C_B$ are used for impedance matching. In Fig. 2, $\Gamma_{La}$, $\Gamma_{Lb}$ and $\Gamma_{Lc}$ show a reflection coefficient, respectively.

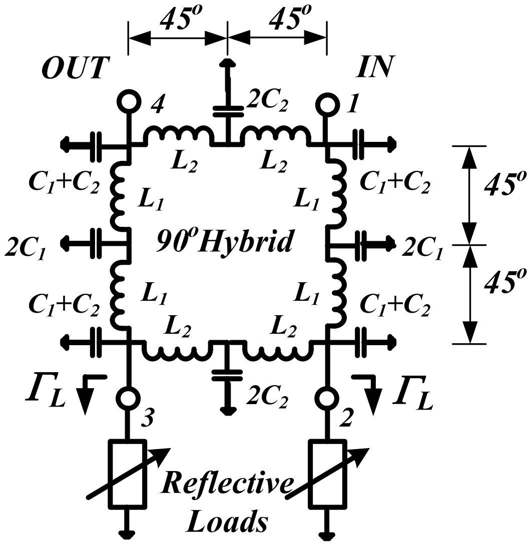
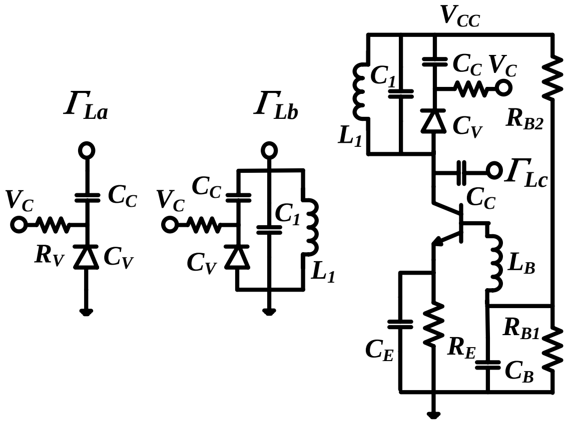


Fig.1 Schematic of the reflection type phase shifter.



***(a) Varactor Diode*** ***(b) Varactor-Loaded LC-Resonator*** ***(c) Active Load***

Fig.2 Schematic of the three different types of the reflective load.

Loci of $\Gamma_{La}$, $\Gamma_{Lb}$ and $\Gamma_{Lc}$ are conceptually and graphically shown in Fig. 3. Now Si varactor diodes with a capacitance ratio of 2.5:1 ($C_{2V}$=15pF, $C_{10V}$=6pF) are used here. A phase shift can be calculated for the circuit of Fig. 2(a). The calculated phase shift was only $32^o$ at 1GHz for $C_C$>>$C_V$, corresponding to the variation of $\Gamma_{La}$ from p to q in Fig. 3. A phase shift was measured for the circuit of Fig. 2(a) and plotted in Fig. 4. A control voltage $V_C$ was varied from 0V to 14V. The measured phase shift $\Delta\Phi$ was normalized by $V_C$=0V. For a variation from $V_C$=2V and $V_C$=10V, a phase shift of $40.5^o$ has been obtained at 1GHz. It is clearly shown in Fig. 3 that $\Gamma_{Lb}$ and $\Gamma_{Lc}$ drastically move from $+180^o$ to $-180^o$ on dotted lines across a resonant frequency of $f_C$. It is because $\Gamma_{Lb}$ and $\Gamma_{Lc}$ vary dynamically from inductive to capacitive across a resonant frequency of $f_C$. Usually, the collector impedance is high and thus $\Gamma_{Lc}$ becomes close to $\Gamma_{Lb}$. For $C_C$>>$C_V$, the resonant frequency $f_C$ of $\Gamma_{Lb}$ and $\Gamma_{Lc}$ is given as follows:

$$f_C = \frac{1}{2\pi\sqrt{L_1(C_1 + C_V)}} \qquad (1)$$

At around $f_C$, however, $|\Gamma_{Lb}|$ becomes smaller due to the parasitic resistance of the resonator. Meanwhile, the active load produces negative resistances in parallel with the varactor-loaded LC-resonator. Thus $|\Gamma_{Lc}|$ becomes larger than $|\Gamma_{Lb}|$ as shown in Fig. 3, which greatly improves the insertion losses or insertion loss variations.

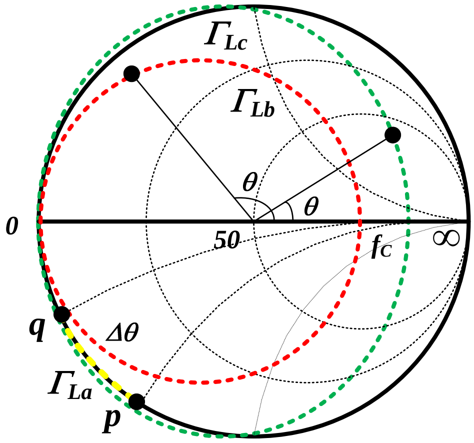


Fig.3 Loci of $\Gamma_{La}$, $\Gamma_{Lb}$ and $\Gamma_{Lc}$

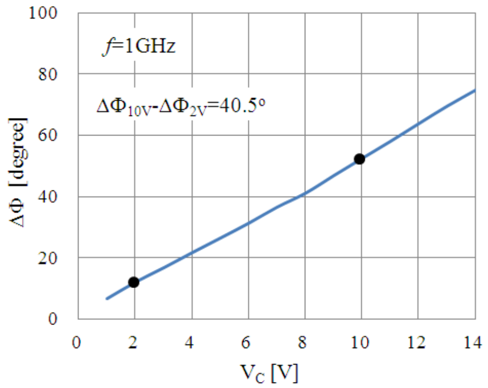


Fig. 4 Measured phase shift ΔΦ of the single varactor diode.

The parallel RC circuit comprised of $R_E$ and $C_E$ provides a positive feedback effect and therefore generates negative impedances. $\Gamma_{Lc}$ of the active load was calculated by using ADS as a function of $C_E$. As a bipolar transistor, SiGe HBTs with an $f_t$ of 25GHz was employed. The calculation was done at 1GHz and the calculated results are plotted in Fig. 5. A magnitude of $\Gamma_{Lc}$ becomes larger than unity above $C_E$ of 23pF. The value of $C_E$ has to be carefully chosen in order to remove the unwanted oscillations. The value of $C_E$ was finally chosen as 24pF. $R_E$ keeps constant with 100Ω for controlling a dc current.

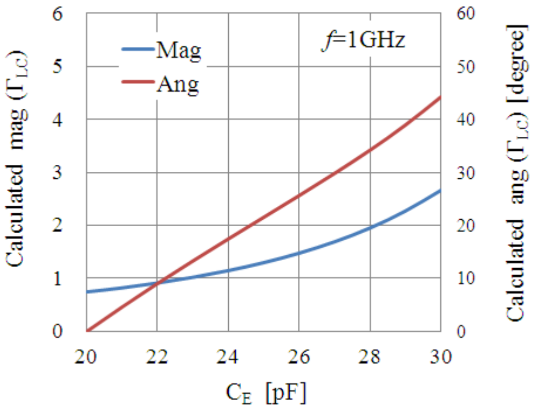


Fig. 5 Calculated $\Gamma_{Lc}$ with a parameter of $C_E$

## 2.2 Circuit Performance of the Reflective Load

To ensure the negative impedance generation, $\Gamma_{Lb}$ and $\Gamma_{Lc}$ were measured for $V_C$ from 0V to 14V and plotted in Figs. 6 and 7, respectively. $\Gamma_{Lb}$ and $\Gamma_{Lc}$ vary from -15dB to 0dB and from -11dB to +0.38dB, respectively, which means that the reflection loss was improved for the active load. It is also clearly shown in Fig. 7 that the negative impedances surrounded by dotted lines were generated. A tuning range of $f_C$ and return losses were also improved in Fig. 7. The measured phase shift $\Delta\Phi$ of $\Gamma_{Lb}$ and $\Gamma_{Lc}$ are plotted in Fig. 8. $\Delta\Phi$ of $\Gamma_{La}$ is also plotted in Fig. 8 for comparison. The measured phase shift $\Delta\Phi$ was normalized by $V_C$=0V. $V_{CC}$ was 1V and the current was 4mA for the active load.

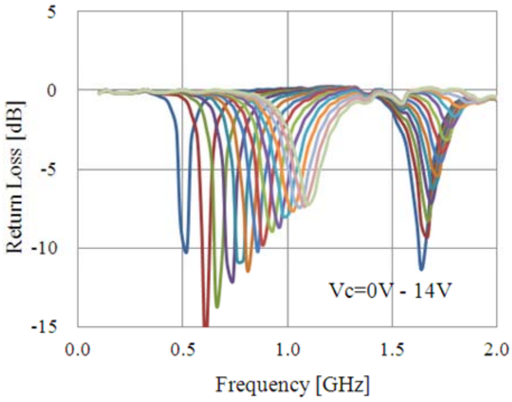


Fig. 6 Measured $\Gamma_{Lb}$ for $V_C$ from 0V to 14V

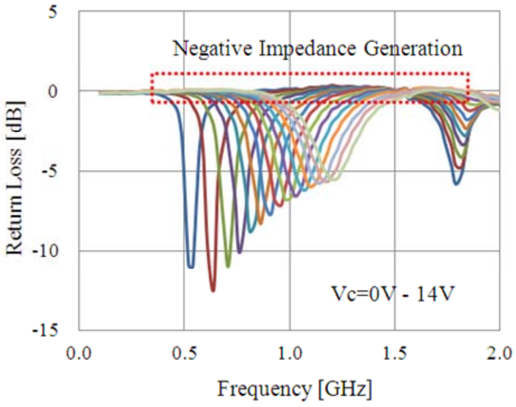


Fig. 7 Measured $\Gamma_{Lc}$ for $V_C$ from 0V to 14V

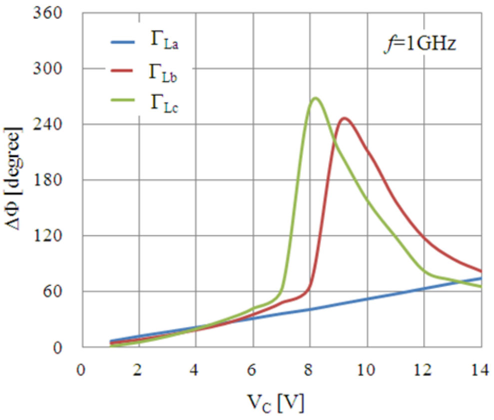


Fig. 8 Measured phase shift ΔΦ of $\Gamma_{La}$, $\Gamma_{Lb}$ and $\Gamma_{Lc}$

It is noted that ΔΦ increases abruptly with $V_C$ and then decreases linearly for both $\Gamma_{Lb}$ and $\Gamma_{Lc}$. A wider phase-shifting range has been achieved for the active load of $\Gamma_{Lc}$ because of low insertion losses and small insertion loss variations. It can be concluded from these data that the active load proposed in this paper greatly contributes to low insertion loss and small insertion loss variations without sacrificing a wide phase-shifting range of the reflection type phase shifter.

## 3 Circuit Fabrication of the Reflection Type Phase Shifter Using Active Load

Photographs of the reflection type phase shifters with three different types of loads are shown in Figs. 9, 10 and 11. The phase shifter was fabricated on the FR-4 substrate with a dielectric constant of 4.5. The thickness of the FR-4 substrate is 1.2mm. 0.35µm SiGe HBT with an $f_t$ of 25GHz (Toshiba MT4S102T), Si varactor diode with a capacitance ratio of 2.5:1 (Toshiba 1SV279), 1005-type chip resistors, inductors and capacitors are mounted on the substrate by soldering. The circuit size is 16 x 16 x 1.2 mm$^3$.

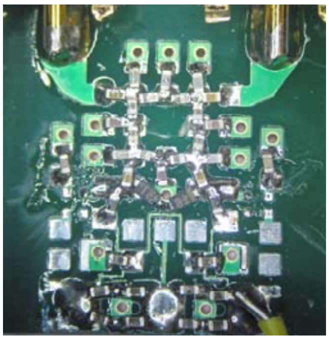


Fig. 9 Photograph of the reflection type phase shifter with single varactor diode

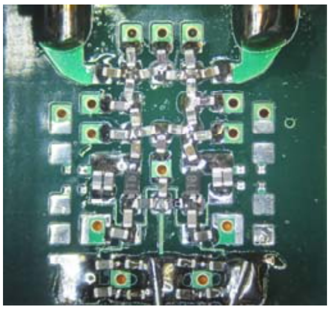


Fig. 10 Photograph of the reflection type phase shifter with the varactor-loaded LC-resonator

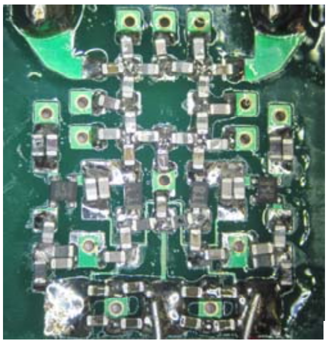


Fig. 11 Photograph of the reflection type phase shifter with the active load

## 4 Circuit Performance of the Reflection Type Phase Shifter Using Active Load

Measured insertion losses of the reflection type phase shifters with three different types of loads are plotted in Figs. 12, 13 and 14, respectively. A control voltage of $V_C$ was varied from 0V to 14V. The current of active load was 4mA when the $V_{CC}$ was 1V.

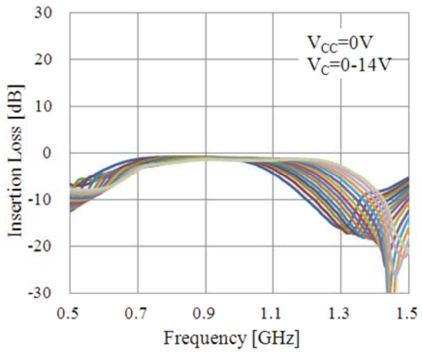


Fig. 12 Measured insertion losses of the reflection type phase shifter with single varactor diode

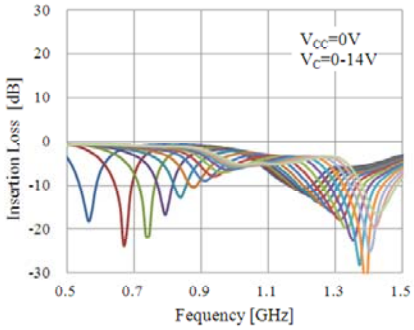


Fig. 13 Measured insertion losses of the reflection type phase shifter with the varactor-loaded LC-resonator

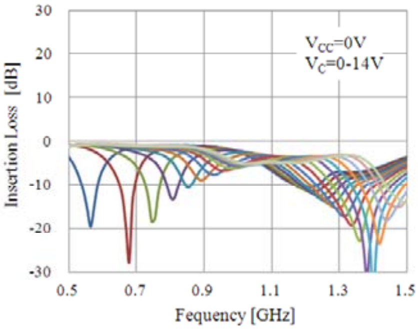


Fig. 14 Measured insertion losses of the reflection type phase shifter with the active load

The measured insertion losses of the reflection type phase shifters with three different types of loads demonstrate 1.37±0.25dB, 4.1±2.0dB and 3.8±1.6dB at 1GHz, respectively. The measured phase shift ΔΦ and insertion loss variation ΔG with a parameter of $V_C$ are plotted in Fig. 15. The maximal ΔΦ were 75.8$^{o}$, 272$^{o}$ and 290$^{o}$ at 1GHz, respectively. In addition, the maximal ΔG were 0.5dB, 4dB and 3.2dB at 1GHz, respectively. In comparison with the single varactor diode, an enhanced improvement on phase-shifting range has been achieved for the active load. In comparison with the varactor-loaded LC-resonator, both phase-shifting range, insertion loss and insertion loss variation have been successfully improved with the use of the active load. As compared with Fig. 8, a control voltage range of $V_C$ is different. A wider control range from 1V to 14V is needed for $V_C$ to achieve the same phase shifting amount because the bandwidth of the 90$^{o}$ hybrid is narrow. The measured return losses were better than 9.5dB for Fig. 2(a), 6dB for Fig. 2(b) and 5.4dB for Fig. 2(c) at 1GHz for all control voltage, respectively. Since the load impedance varies drastically for Figs. 2(b) and (c), the return loss due to the imbalance between loads has become worse.

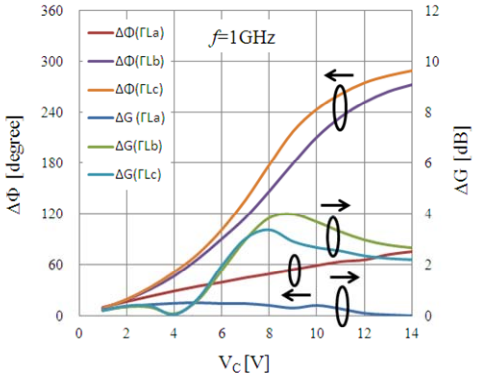


Fig. 15 Measured phase shift ΔΦ and insertion loss variation ΔG with a parameter of $V_C$

## 5 Comparisons of Performances

A comparison of performances between the previously published reflection type phase shifters [6]-[12] and this work is summarized in Table I. It has a tendency that a wider relative phase shift of greater than $300^o$ produces a higher insertion loss of greater than 4dB. Although the reference [11] shows a low insertion loss of 2.6dB at 2.5GHz, this is simulated data. It can be noted from this viewpoint that this work using the active load has provided an alternative design choice to break through the tradeoffs between phase shift and amplitude variation.

Table 1 Comparison of performances between the previously published reflection type phase shifters and this work.

| References | Frequency | Phase Shift | Loss | Loads |
|---|---|---|---|---|
| [6] | 6-18GHz | $120^o$ | 2.7±1.3dB | Multiple Varactors Series LC Circuit |
| [7] | 1.95-2.15GHz | $400^o$ | <4dB | Multiple (six) Varactors |
| [8] | 2GHz | $407^o$ | 4.4±0.2dB | Multiple Varactors Distributed Transformer |
| [9] | 2.44-2.55GHz | $340^o$ | 10.6±2dB | Multiple Varactors Lumped Transformer |
| [10] | 0.5-30GHz | $183\pm3^o$ | 3.7±0.6dB | Switching Series and Parallel LC-Circuits |
| [11] | 2.5GHz | $360^o$ | 2.6dB | PIN Diode Switching Series and Parallel LC-Circuits |
| [12] | 24GHz | $360^o$ | 12.5±1.2dB | Transformer-based Quadrature Coupler |
| This work | 0.9-1.1GHz | $290^o$ | 3.8±1.6dB | Active Loads |

## 6 Conclusions

A new reflection-type phase shifter using active loads has been demonstrated in this paper for realizing a wide phase-shifting range and small amplitude variations. With the active load using common-emitter HBTs, varactor-loaded LC-resonators and RC-feedback circuits, both insertion loss and insertion loss variation have been mainly improved in comparison with the conventional reflection type phase shifters based on LC-resonators. In addition, as compared with the traditional reflection type phase shifter using a single varactor diode, a significant improvement on phase-shifting range has been achieved. It can be concluded from these results that the active load proposed in this paper would be one of the candidates as an analog phase shifter for use in the future wireless, aerospace, microwave and millimeter-wave communication, sensors and radar systems.

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