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L-Band SiGe HBT Differential Variable Gain Amplifiers Using Capacitance-Variable/Selectable Bridged-T Attenuators

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Abstract

L-band SiGe HBT differential variable gain amplifiers (VGAs) with analog or digital control have been developed to realize fine tuning of gain. These VGAs use capacitance-variable/selectable bridged-T attenuators in the design of a series feedback circuit of the differential amplifier and achieve continuous or discrete gain variations by varying or switching the bridging-capacitances. Contrary to the traditional VGAs using a variation of gm or resistance, high gain can be expected because of the positive feedback effect through the bridging-capacitance. An L-band continuously variable gain amplifier using a capacitance-variable bridged-T attenuator has achieved a gain variation of 5dB with a phase variation of 11 degrees at 1.2GHz. On the other hand, an L-band 4-bit VGA has achieved a gain variation of 7.6dB with a phase variation of 3.1 degrees at 1.4GHz. This is the first report on the VGAs using a variation of the reactive element.

Keywords: variable gain amplifier, differential, microwave, bridged-T attenuator, SiGe HBT

1 Introduction

With the recent global progress in wireless and satellite communication systems, variable gain control becomes necessary in RF, IF and baseband frequencies for a wide dynamic range of transmitted and received signals [1]. In addition, the recent and future aerospace or communication systems require precise amplitude control in particular to improve transmit and receive sidelobe levels for the modern electromagnetic compatibility demands [2]. To meet these requirements, a variety of VGAs have been actively developed. They are classified into two groups. One group utilizes a variation of gm by controlling bias conditions including voltage [3], [4], current [5], [6], or transistor size [7], [8]. The other group utilizes a variation of resistance for use in the negative feedback circuit [9], lossy match circuit [10], or attenuators [11]. Most of these VGAs utilize a variation of gm or resistance and thus the gain becomes relatively low. In addition, digital control is preferred instead of analog control since the interface with digital control circuits becomes easy. Thus the multi-bit VGAs usually produce a larger circuit size. The authors have presented two types of the 4-bit differential variable gain amplifiers employing bridged-T attenuators in the design of a series feedback circuit for coarse tuning of gain [12] and for fine tuning of Gain [13]. Since the 4-bit VGA in [12] cascades four different gain stages, high dynamic range and high linearity have been achieved but the circuit size was large. On the other hand, since the 4-bit VGA in [13] incorporates a single-stage design with a resistance-selectable bridged-T attenuator, a miniaturized size has been achieved but the gain was relatively low. In order to address these problems, a novel design approach for the differential variable gain amplifiers is proposed in this paper. Instead of the resistance-based bridged-T attenuator, reactance-based capacitance-variable/selectable bridged-T attenuators are incorporated into the design of a series feedback circuit to improve gain and make the circuit size smaller. Since the capacitance-variable/selectable bridged-T attenuator provides a positive feedback effect, high gain can be expected. Two types of the differential variable gain amplifiers with analog or digital control are presented. The analog type incorporates a capacitance-variable bridged-T attenuator and thus produces a continuous gain variation. The digital type utilizes a capacitance-selectable bridged-T attenuator and thus provides a discrete gain variation. The design approach presented in this paper can be considered to be suitable for the differential VGAs with high gain, miniaturized size, and fine tuning of gain for relatively narrow dynamic range.

2 Circuit Design

Schematic diagrams of the differential variable gain amplifiers using capacitance-variable/selectable bridged-T attenuators are shown in Figs. 1 and 2. A capacitance-variable bridged-T attenuator is employed in the design of a series feedback circuit of the differential amplifier in Fig. 1 and a capacitance-selectable bridged-T attenuator in Fig. 2. R_E, R_S and R_C consist of a Tee attenuator. R_L and R_C play a role of load impedance and current source, respectively. C_S is a variable bridging-capacitance.

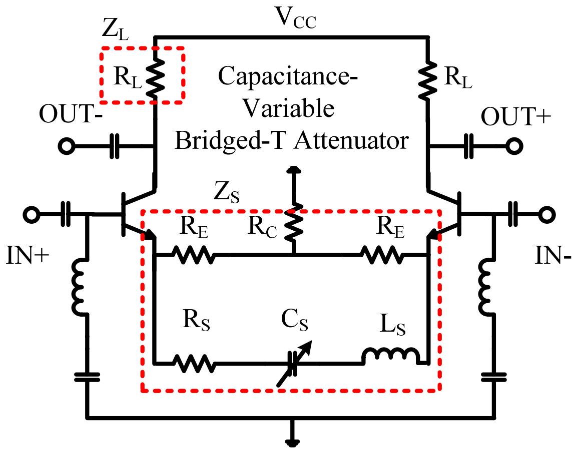

Fig. 1 Schematic diagram of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

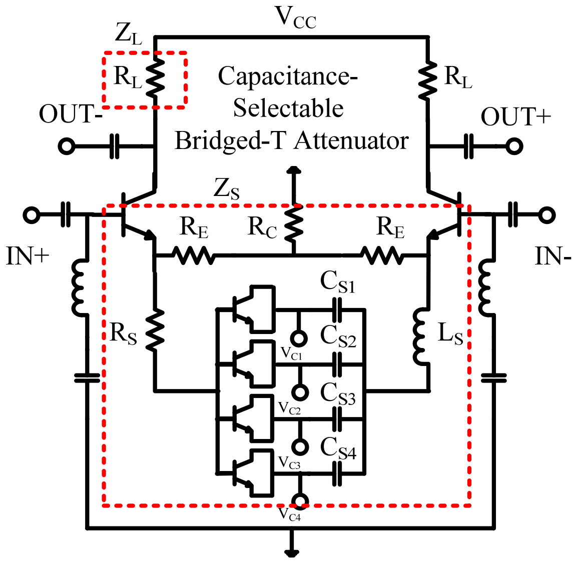

Fig. 2 Schematic diagram of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

Now Z_L and Z_S are expressed as load impedance and source impedance connected between a transistor-pair, the gain of the amplifier can be approximately given by the following equations:

$$G = \frac{2Z_L}{Z_S}$$

$$= \frac{R_L}{R_E} + \frac{2R_L}{R_S + j\omega\left\{1 - \left(\frac{\omega_C}{\omega}\right)^2\right\}}$$

$$= \mathrm{Re}[G] + j\,\mathrm{Im}[G] \tag{1}$$

$$\mathrm{Re}[G] = R_L\left[\frac{1}{R_E} + \frac{2R_S}{R_S{}^2 + \left[\omega L_S\left\{1 - \left(\frac{\omega_C}{\omega}\right)^2\right\}\right]}\right] \tag{2}$$

$$\mathrm{Im}[G] = -2R_L\frac{\omega L_S\left\{1 - \left(\frac{\omega_C}{\omega}\right)^2\right\}}{R_S{}^2 + \left[\omega L_S\left\{1 - \left(\frac{\omega_C}{\omega}\right)^2\right\}\right]} \tag{3}$$

$$\omega_C = \frac{1}{\sqrt{L_S C_S}} \tag{4}$$

In Eq. 4, ω_C denotes a cutoff frequency. The gain G_{dB} and phase θ can be written as follows:

$$G_{dB} = 20\log|G| = 20\log\sqrt{\mathrm{Re}[G]^2 + \mathrm{Im}[G]^2} \tag{5}$$

$$\theta = \tan^{-1}\frac{\mathrm{Im}[G]}{\mathrm{Re}[G]} \tag{6}$$

If $\omega = \omega_C$ then the gain provides the maximum value as

$$G_{\max} = R_L\left(\frac{1}{R_E} + \frac{2}{R_S}\right) \tag{7}$$

It can be noted from Eq. 7 that a smaller value of R_E and R_S and a larger value of R_L provide higher gain. If it is assumed that R_E, R_S and R_L keep constant, then the gain in Eq. 1 can be varied with ω_C, which is graphically shown in Fig. 3. In Fig. 3, $\omega = \omega_C$ provides the maximum gain. The gain can be varied with ω_C.

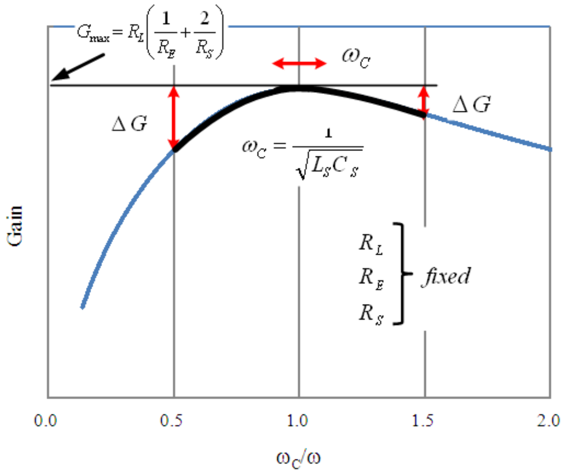

Fig. 3 Gain of the differential VGA

Next let us calculate the gain G_{dB} and phase θ in Eqs. 5 and 6 based on the element values of Table 1 for the frequency from 0.1 to 3GHz. The value of C_S was chosen as 6, 8, 10, 12 and 14pF. The calculated G_{dB} and Δθ are plotted in Figs. 4 and 5, respectively. Δθ is defined as a deviation from C_S=6pF.

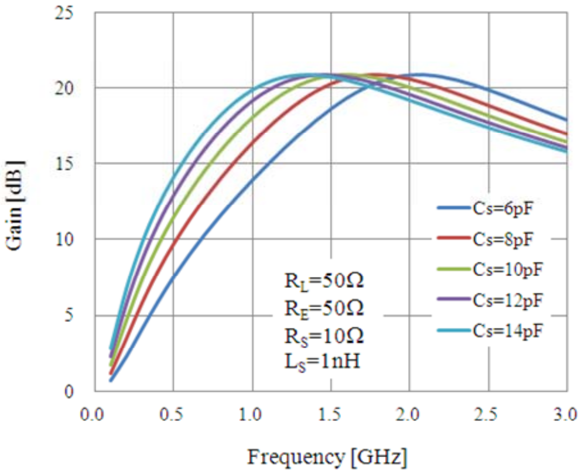

Fig. 4 Calculated G_{dB}

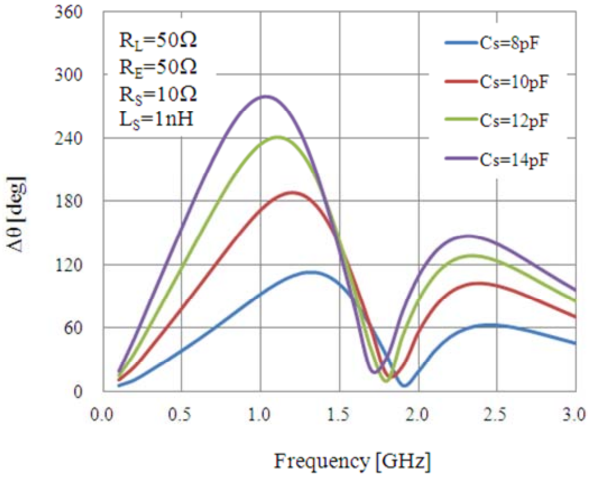

Fig. 5 Calculated Δθ

It is clearly shown that the gain can be varied with C_S from 6 to 14pF at a fixed frequency. Around the series resonant frequency, maximum gain and small phase variation are obtained. On the other hand, at around 1GHz, large gain and phase variations are obtained. The element values in Table 1 were actually used for the circuit design of the amplifiers in Figs. 1 and 2. The value of C_S from 6 to 15pF is a variable capacitance of the Si varactor diode with a capacitance ratio of 2.5:1. The value of C_{S1} to C_{S4} is designed so that the total capacitance shows 1 to 15pF by 1dB step, which corresponds to C_S in Table 1.

Table 1 Element values of the differential VGAs

Element	Value
R_L [Ω]	50
R_E [Ω]	50
R_S [Ω]	10
L_S [nH]	1
C_S [pF]	6-15
C_{S1} [pF]	1
C_{S2} [pF]	2
C_{S3} [pF]	4
C_{S4} [pF]	8

3 Circuit Simulation

The analysis presented in the previous chapter is an ideal case and thus the series feedback effect or the circuit losses are not taken into account. In order to address this problem, the circuit simulation was accomplished for the circuit in Fig. 1 by using HP-EESOF's ADS. The circuit simulation was done by using the element values in Table 1 and V_{CC} of 6V. SPICE models were used for the 0.35μm SiGe HBT with an f_t of 25GHz (Toshiba MT4S102T). The simulated results are plotted in Fig. 6. It is clearly shown that as C_S decreases, the gain becomes higher because of the positive feedback effect.

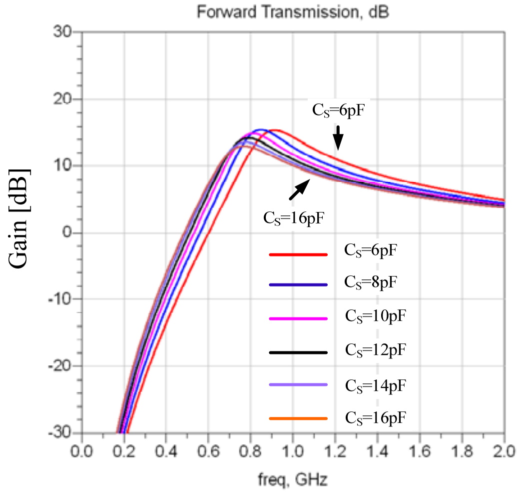

Fig. 6 Simulated gains for C_S of 6 to 16pF

4 Circuit Fabrication

Photographs of the differential VGAs using capacitance-variable/selectable bridged-T attenuators are shown in Figs. 7 and 8, respectively. The VGAs were fabricated on the FR-4 substrate with a dielectric constant of 4.5. 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.

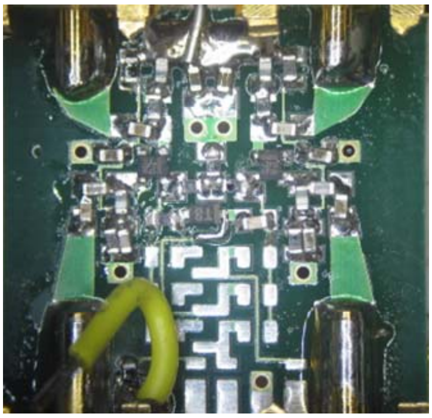

Fig. 7 Photograph of the differential VGA using a capacitance-variable bridged-T attenuator (analog type) 16 x 16 x 1.2 mm^3

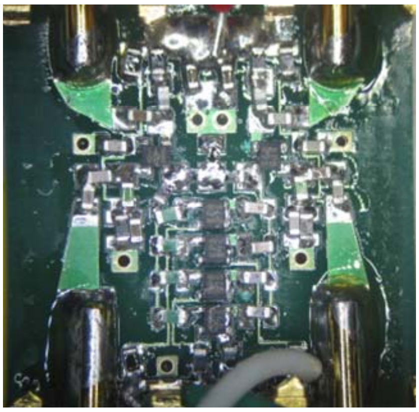

Fig. 8 Photograph of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type) 16 x 16 x 1.2 mm^3

5 Circuit Performance

5.1 Differential VGA using capacitance-variable bridged-T attenuator (analog type)

Measured gain, phase variation, input and output return losses are shown in Figs. 9 to 12, respectively. A maximum gain variation of 10dB and a phase variation of 55.5 degrees have been measured at 0.87GHz. The positive feedback amount is large at 0.86GHz and thus a variation of phase, input and output return losses becomes worse. As the frequency increases, a phase variation was improved down to 11 degrees with a gain variation of 5dB at 1.2GHz. A variation of input and output return losses also becomes small. Bias conditions are V_{CC} of 6V, V_C of 0 to 16V and I_C of 9mA. In Fig. 10, a phase variation is expressed as a deviation from the data of V_C=0V.

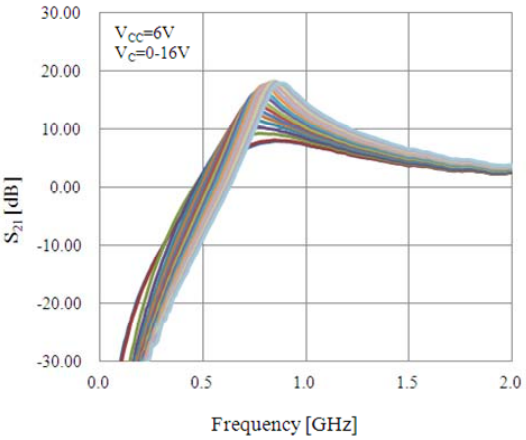

Fig. 9 Measured gains of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

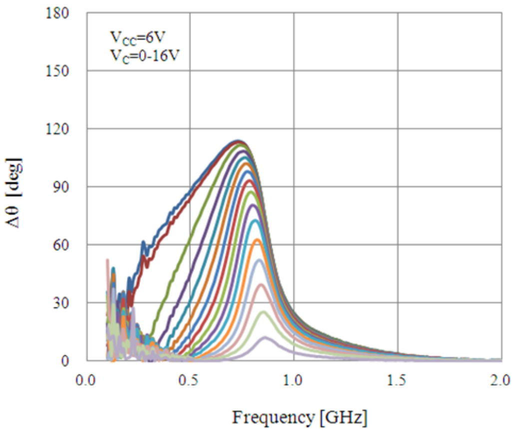

Fig. 10 Measured phase variations of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

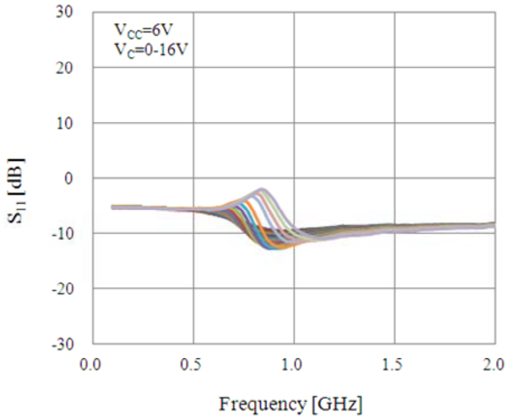

Fig. 11 Measured input return loss of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

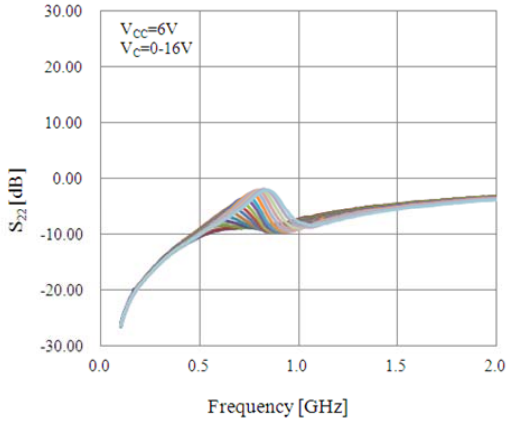

Fig. 12 Measured output return loss of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

5.2 Differential VGA using capacitance-selectable bridged-T attenuator (digital type)

Measured gain, phase variation, input and output return losses are demonstrated in Figs. 13 to 16, respectively. 4-bit, 16-states performances are plotted. If a control voltage of V_{C1} to V_{C4} is 0V, the switch becomes "ON" state. A maximum gain variation of 11.8dB and a phase variation of 40 degrees have been measured at 1.02GHz, where the positive feedback amount is large. Meanwhile, as the frequency increases, a phase variation was improved down to 3.1 degrees with a gain variation of 7.6dB at 1.4GHz. A variation of input and output return losses also becomes small. Bias conditions are V_{CC} of 6V and I_C of

9mA. In Fig. 14, a phase variation is expressed as a deviation from the data of a total C_S of 15pF.

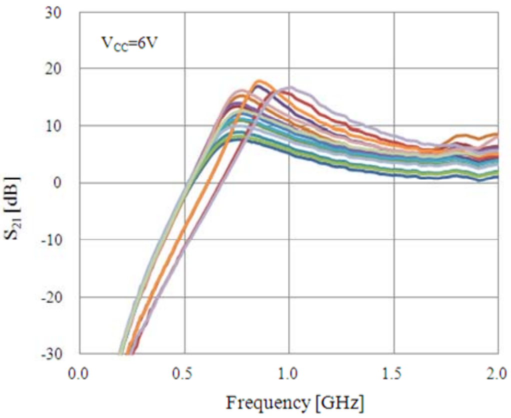

Fig. 13 Measured input return loss of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

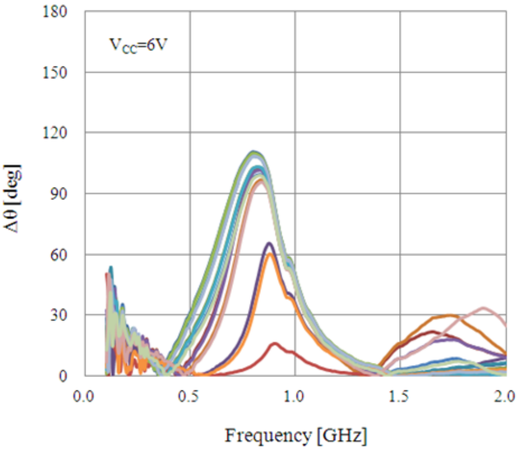

Fig. 14 Measured output return loss of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

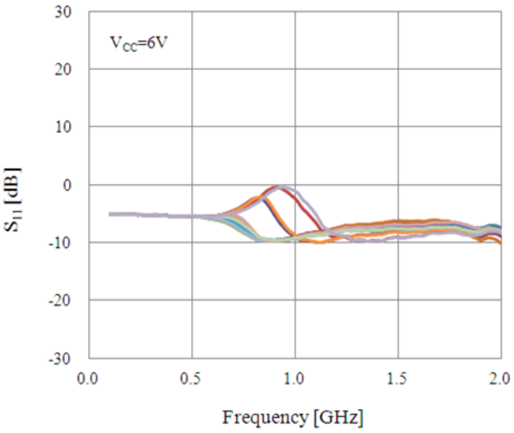

Fig. 15 Measured input return loss of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

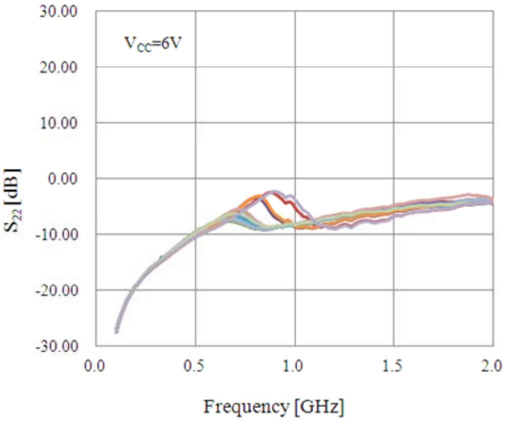

Fig. 16 Measured output return loss of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

5.3 Noise figure performance

Noise figures of the differential VGAs using capacitance-variable/selectable bridged-T attenuators were measured from 0.8 to 1.4GHz for both amplifiers. The measured noise figure performances are shown in Figs. 17 and 18, respectively. V_{CC} is 6V. V_C varies from 3 to 13V for the analog type. I_C was 9mA. In Fig. 17, the measured noise figure was better than 4.7dB at 1.2GHz. Meanwhile, in Fig. 18, the measured noise figure was better than 6.4dB at 1.4GHz for all gain states. I_C was also 9mA.

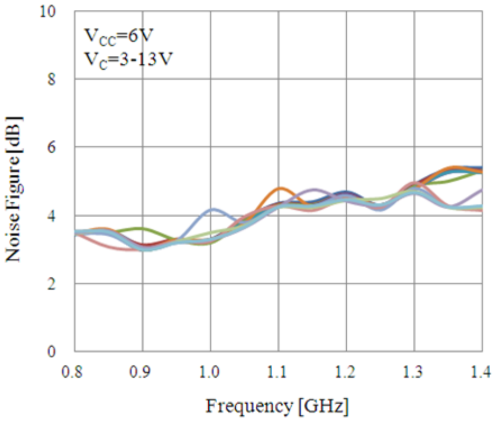

Fig. 17 Measured noise figure of the differential VGA using a capacitance-variable bridged-T attenuator (analog type)

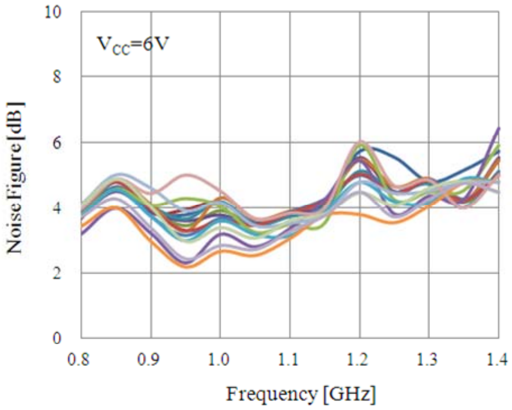

Fig. 18 Measured noise figure of the differential VGA using a capacitance-selectable bridged-T attenuator (digital type)

5.4 IIP_3

Usually the worse case for IIP_3 is to show the highest gain. The measured IIP_3 with two tones of 0.95 and 1.05GHz have shown the minimum value of -5dBm at a V_{CC} of 6V and an I_C of 9 mA for both amplifiers.

6 Conclusions

Two types of the L-band SiGe HBT differential variable gain amplifiers (VGAs) with analog or digital control have been demonstrated for fine tuning of gain. Since the VGAs use capacitance-variable/selectable bridged-T attenuators in the design of a series feedback circuit of the differential amplifier, high gain and miniaturized size have been realized without making a serious effect on the input and output matches. The VGA using a capacitance-variable bridged-T attenuator has achieved a gain variation of 5dB and a phase variation of 11 degrees at 1.2GHz. Meanwhile, the 4-bit VGA has achieved a gain variation of 7.6dB and a phase variation of 3.1 degrees at 1.4GHz. This is the first report on the VGAs using a variation of the reactive element. The design approach based on variable reactive elements can be considered to be one of the candidates for achieving high gain, miniaturized size, and fine tuning of gain of VGAs for relatively narrow dynamic range.

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