

An L-Band SiGe HBT Vector Modulator Using Lumped-Element $180^\circ/90^\circ$ Hybrids and Wilkinson Power Dividers for High Stability and Small Amplitude/Phase Errors

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Abstract:

An L-band SiGe HBT vector modulator has been developed for the next generation wireless radios using active phased array antennas and adaptive beam forming networks. It employs $180^\circ/90^\circ$ hybrids for achieving quadrature phase shifting, four variable gain amplifiers for controlling gain, and Wilkinson power dividers for combining vectors. The amplitudes of two of the four signal paths with a phase offset of 90° are weighed and combined to obtain a full 360° phase shifting. High stability and small amplitude/phase errors can be expected since the $180^\circ/90^\circ$ hybrids and Wilkinson power dividers provide high isolation between ports. A collector drive is used for switching amplifiers to achieve high impedance and low insertion loss. Lumped elements are employed in the design of the $180^\circ/90^\circ$ hybrids and Wilkinson power dividers for achieving a miniaturized size. Lookup tables of the control voltages are generated from calibrating four signal paths. This lookup table can be easily extended to the electrical, environmental or process changes. The vector modulator shows a maximum gain error of less than 1dB and a maximum phase error of less than 2° for a full 360° phase shifting at 1GHz.

Index Terms:

vector modulator, variable gain amplifier, 180° hybrid, 90° hybrid, Wilkinson power divider, phase shift.

I. INTRODUCTION

Recently, the active phased array antennas combined with adaptive beam forming networks are actively researched for the next generation wireless radios [1], [2]. In order to make an accurate steering of multiple beams, phase shifting becomes crucial from the viewpoint of an accurate tracking of the target as well as high efficiency of the power combining. Up to now, a variety of passive phase shifters have been reported [3]. They are reflection type [4], switched-line type [5], loaded-line type [6], and LPF/HPF-switching type [7]. These passive phase shifters are well-suited for the phased array

modules because of their low power consumption and high linearity. However they are generally lossy and hence require additional buffer amplifiers. From the viewpoint, the active phase shifters with gains are preferable for realizing a miniaturized size of the phased array modules. As an active phase shifter, the vector modulators are actively researched because of their full 360° phase variation, wide bandwidth, and high gain [8], [9], [10]. The reference [8] uses two of the four signal paths with a phase offset of 90° and the references [9], [10] employ two of the three signal paths with a phase offset of 120° for achieving a full 360° phase shifting. These vector modulators, however, show a poor isolation between paths since no isolation resistor is employed, which seriously makes the modulator unstable and sometimes

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produces unacceptable gain or phase errors.

To address this problem, the $180^\circ/90^\circ$ hybrids [11], [12] are used for quadrature phase shifting and the Wilkinson power dividers [13] are employed for vector combining. Since the $180^\circ/90^\circ$ hybrids and the Wilkinson power dividers employ an isolation resistor for terminating odd mode signals, high isolation, high stability and small amplitude/phase errors can be achieved. In addition, a miniaturized size can be expected by incorporating lumped elements into the design of these circuits.

Vector modulators can provide a full 360° phase shifting by weighting and combining the signal paths with defined phase offsets. Variable gain amplifiers are required to control the amplitudes of the signal paths without affecting the insertion phase performance. But actually the insertion phase varies drastically with the gain control. Therefore, it becomes crucial how to deal with the phase deviation across the gain variation. To address this problem, the lookup tables of the control voltages are generated from calibrating all signal paths. In this paper, the lookup tables including 20×20 sets of the control voltages are generated for 0° to 90° , 90° to 180° , 180° to 270° , and 270° to 360° phase shifting. The gain and phase errors can be greatly reduced with the proper selection of the control voltages.

II. COMPONENTS CONSISTING OF THE VECTOR MODULATOR

A block diagram of the vector modulator is shown in Fig. 1. It is comprised of the $180^\circ/90^\circ$ hybrids, the Wilkinson power dividers and the variable gain amplifiers. Input signals are split into four vectors with a phase offset of 90° through the $180^\circ/90^\circ$ hybrids. Then the amplitudes of two of the four vectors are weighed and combined to obtain a full 360° phase shifting through the variable gain amplifiers and the Wilkinson power dividers. A vector combining is illustrated in Fig. 2. For example, a phase shift from 0° to 90° can be accomplished by combining vectors G_1 and G_2 .

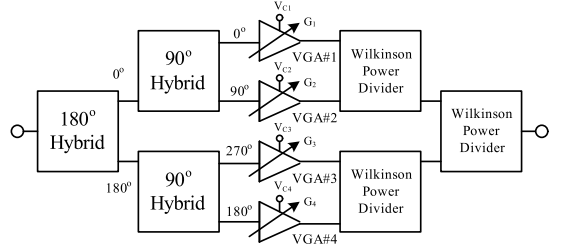


Fig. 1. Block diagram of the vector modulator

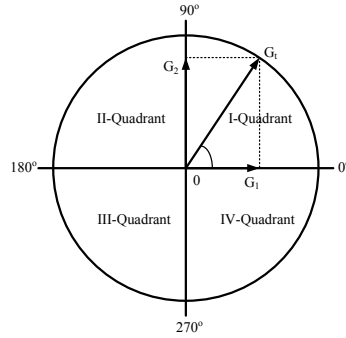


Fig. 2. Vector combining: G_1 and G_2 are combined to produce G_t . The angle θ of G_t can be varied by weighting G_1 and G_2 .

Contrary to the conventional vector modulators [9], [10] with a phase offset of 120° , four signal paths with a phase offset of 90° , the $180^\circ/90^\circ$ hybrids and the Wilkinson power dividers are used in order to achieve high stability and small amplitude/phase errors. Since only two of the four vectors are combined, the gain becomes smaller than [9], [10]. In order to improve gain, a collector voltage in place of a base voltage is switched "ON" or "OFF" when switching amplifiers since high isolation and high impedance performances can be obtained when a collector voltage is zero ("OFF" state).

A. Variable Gain Amplifier

A schematic diagram of the variable gain amplifier is shown in Fig. 3. A combination of the negative feedback and lossy match circuits is used to achieve a flat gain, low input and output VSWRs from 0.5 to 1.5GHz. The amplifier employs a cascode connection of $0.35\mu\text{m}$ SiGe HBTs with an f_t of around 25GHz

to control gain. VCC is a supply voltage of 1.45V and VC is a control voltage from 0.6 to 1.0V. The measured gain and phase variations are plotted in Fig. 4. Within a VC from 0.6 to 1.0V, the gain and phase variations are 40dB and 96° at 1GHz, respectively.

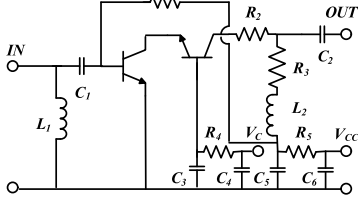


Fig. 3. Schematic diagram of the variable gain amplifier

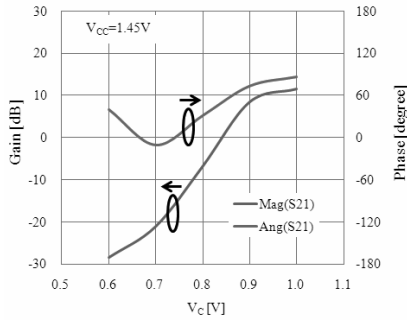


Fig. 4. Measured gain and phase variations

B. 180° Hybrid

A schematic diagram of the 180°-hybrid [11] is shown in Fig. 5. Port 1 is an input port. An input signal is split into two-ways through LPF/HPF with 180° out of phase and delivered to Ports 2 and 4. Port 3 is an isolation port which is terminated by

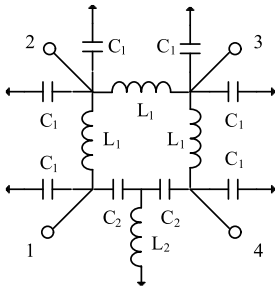


Fig. 5. Schematic diagram of the 180°-hybrid [11]

50Ω. The circuit parameters were designed so that the center frequency becomes 1GHz. The measured S-parameters and phase difference between Port 2 and Port 4 ($\Delta\theta$) are shown in Fig. 6. A phase difference was 176.4° at 1GHz.

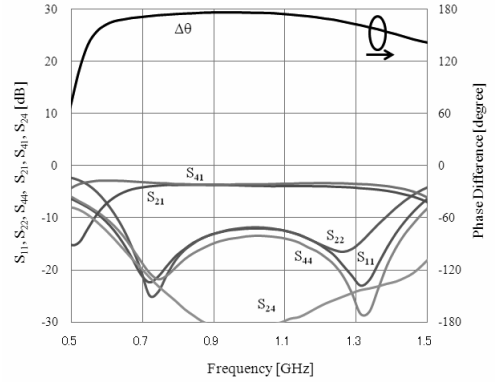


Fig. 6. Measured S-parameters and phase difference

C. 90° Hybrid

A schematic diagram of the 90o-hybrid [12] is shown in Fig. 7. Port 1 is an input port. An input signal is split into Port 3 and Port 4 with 90° out of phase. Port 2 is an isolation port which is terminated by 50Ω. The center frequency and the coupling factor were designed as 1GHz and -3dB, respectively. The measured S-parameters and phase difference between Port 3 and Port 4 ($\Delta\theta$) are shown in Fig. 8. A phase difference was 88.3° at 1GHz. The measured isolation S_{23} was 19dB at 1GHz, which does not produce unwanted amplitude and phase errors because the variation of load impedances is small.

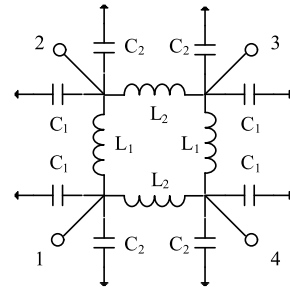


Fig. 7. Schematic diagram of the 90°-hybrid [12]

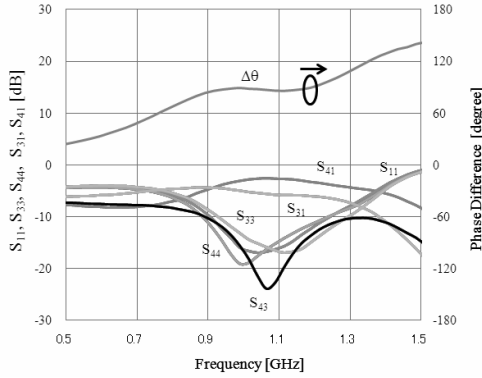


Fig. 8. Measured S-parameters and phase difference

D. Wilkinson Power Divider

A schematic diagram of the Wilkinson power divider [13] is shown in Fig. 9. An input signal to Port 1 is split into Port 2 and Port 3 with equal amplitude and in phase. By contrast, input signals

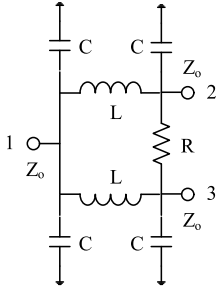


Fig. 9. Schematic diagram of the Wilkinson power divider [13]

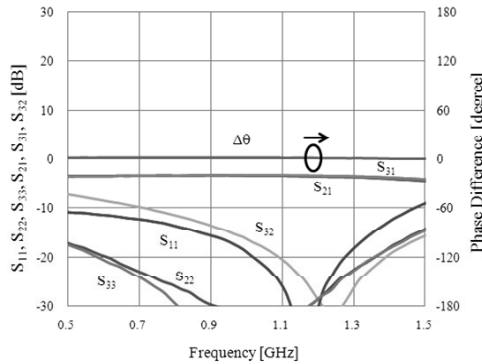


Fig. 10. Measured S-parameters and phase difference

to Port 2 and Port 3 are combined and delivered to Port 1. An isolation resistor with 50Ω is employed between Ports 2 and 3 to suppress the odd mode signals. The center frequency was designed as 1GHz. The measured S-parameters and phase difference between Port 2 and Port 3 ($\Delta\theta$) are shown in Fig. 10. A phase difference was 2.1° at 1GHz.

III. VECTOR MODULATOR

Based on the schematic diagrams of Figs. 1, 3, 5, 7 and 9, the vector modulator has been designed to give a gain of -3dB , a gain error of less than 2dB and a phase error of less than 2° at 1GHz. A photograph of the vector modulator is shown in Fig. 11. The vector modulator was fabricated on the FR-4 substrate with a dielectric constant of 4.5. The 1005-type chip resistors, capacitors, and inductors are mounted on the substrate by soldering. A surface mount type of the SiGe HBT (Toshiba MT4S102T) described in the previous chapter is employed. The circuit size is $32 \times 16 \times 1.2 \text{ mm}^3$.

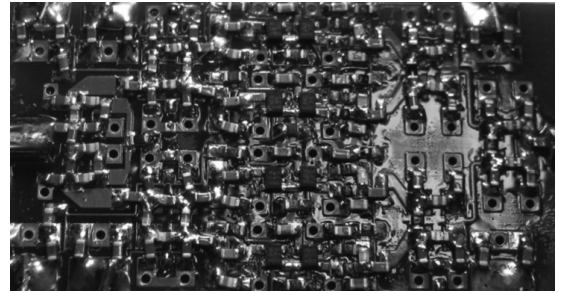


Fig. 11. Photograph of the vector modulator

A procedure of calibration and generation of lookup tables are as follows:

- 1) S-parameters are measured for four signal paths as shown in Fig. 1 where V_{CC} of 1.45V and V_C of 0.6 to 1.0V are supplied to "ON"-VGAs and V_{CC} of 0V is supplied to "OFF"-VGAs. A step size of V_C is 0.1V. G_1 , G_2 , G_3 and G_4 are obtained here.
- 2) The combined gain G_t is calculated from G_1 to G_4 . For example, take a look at the 0° to 90° phase shifting in Fig. 2. The combined gain G_t

is calculated from G_1 and G_2 . Then the control voltages of V_{C1} and V_{C2} are selected to meet the condition that the insertion phase of G_i moves from 0° to 90° with a resolution of less than 2° and the gain keeps within the range from -4 to -2 dB at 1 GHz.

- 3) Lookup tables are generated for 20×20 sets of the control voltages of V_{C1} and V_{C2} , which must include the optimum points. A large part of the lookup table is shown in Table I. From this table, the optimum control voltages of V_{C1} and V_{C2} have to be selected. In Table I, the selected points are shown with “gain/angle”. The other points represented as “*” are not selected.

Table I. Lookup tables of the control voltages

	V_{C1} [V]											
	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01
0.80	*	*	*	*	*	*	*	*	*	*	*	*
0.81	*	*	*	*	*	*	*	*	*	*	*	*
0.82	*	*	*	*	*	*	*	*	*	*	*	*
0.83	*	*	*	*	*	*	*	*	*	*	*	*
0.84	*	*	*	*	*	*	*	*	*	*	*	*
0.85	*	*	*	*	*	*	*	*	*	*	*	*
0.86	*	*	*	*	*	*	*	*	*	*	*	*
0.87	*	*	*	*	*	*	*	*	*	*	*	*
0.88	*	*	*	*	*	*	*	*	*	*	*	*
0.89	*	*	*	*	*	*	*	*	*	*	*	*
0.90	*	*	*	*	*	*	*	*	*	*	*	*
0.91	*	-2.7/40	*	*	*	*	*	*	*	*	*	*
0.92	*	-3.0/50	*	*	*	*	*	*	*	*	*	*
0.93	*	-3.2/59	*	*	*	*	*	*	*	*	*	*
0.94	*	-3.1/71	*	*	*	*	*	*	*	*	*	*
0.95	-3.2/80	*	*	*	*	*	*	*	*	*	*	*
0.96	*	*	*	*	*	*	*	*	*	*	*	*
0.97	*	*	*	*	*	*	*	*	*	*	*	*
0.98	*	-3.2/91	*	*	*	*	*	*	*	*	*	*
0.99	*	*	*	*	*	*	*	*	*	*	*	*

Gain[dB] / Angle[degree]

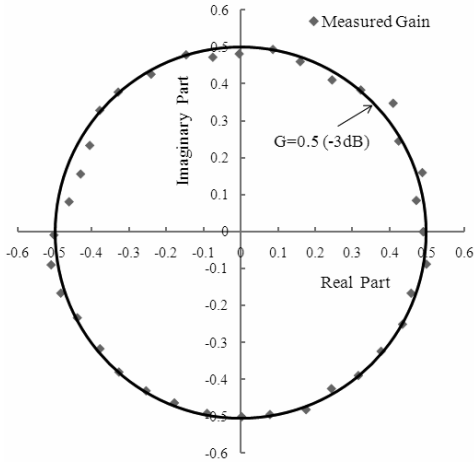


Fig. 12. Measured constellation of the vector modulator

The measured constellation of the vector modulator is plotted in Fig. 12. The vector modulator has presented a maximum gain error of less than 1 dB and a maximum phase error of less than 2° for a full 360° phase shifting at 1 GHz. To reduce amplitude and phase errors, much more precise control of V_{C1} and V_{C2} as well as better phase matching of the 180° - and 90° -hybrids are required. A fast switching time with few nano seconds is available because an electrical controlling of voltages is employed in the bias circuit.

IV. Conclusion

An L-band SiGe HBT vector modulator has been presented. It employs $180^\circ/90^\circ$ hybrids for achieving quadrature phase shifting, four variable gain amplifiers for controlling gain, and Wilkinson power dividers for combining vectors to achieve small amplitude/phase errors. The amplitudes of two of the four signal paths with a phase offset of 90° were weighed and combined. In addition, lookup tables of the control voltages were generated from calibrating four signal paths. As a result, the vector modulator has shown a maximum gain error of less than 1 dB and a maximum phase error of less than 2° for a full 360° phase shifting at 1 GHz. The techniques presented in this paper can be easily applied to the large-scale, high-volume, low-cost SiGe or CMOS ICs.

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