Proceedings of **ITC-CSCC 2000**, Pusan, Korea

Development of a New Active Phase Shifter

S.J. Kim and N.H. Myung

Department of Electrical Engineering
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Kusong-dong, Yusung-gu, Taejon, Korea

Abstract— **In this paper, a new active phase shifter is proposed using a vector sum method, and it is shown that the proposed phase shifter is more efficient than the others in size, power, number of circuits, and gain. Also a unique digital phase control method of the circuit is suggested. The proposed scheme was designed and implemented using a Wilkinson power combiner/divider, a branch line 3dB quadrature hybrid coupler and variable gain amplifiers (VGAs) using dual gate FETs (DGFETs). Furthermore, it is also shown that the proposed scheme is more efficient and works properly with the digital phase control method.**

I. INTRODUCTION

There are two kinds of active phase shifters. One is controling the phase of the RF signal varying the bias voltage of the gate using the characteristics of the DGFET itself [1]. This type of phase shifter has many problems in applying to practical systems because of the small phase shift range and the large variation of the gain. The other type of phase shifter uses a vector sum method [3][4][5]. This method is based on the principle of the vector sum of phase separated variable vectors to achieve a 360° phase change. Variable phase shifts and gains are obtained by adjusting the relative amplitudes of the vectors. In the vector sum method, VGAs are often realized using DGFETs. Recently a quadrature active phase shifter using single gate FETs was also reported [6].

Previously reported active phase shifters using a vector sum method have, however, large power loss due to the architectural schemes and inefficiency in using VGAs. In this paper, a new active phase shifter was designed and implemented, which can solve these problems. It was also shown that the presented scheme is more efficient and works properly with the suggested unique digital phase control method.

II. A NEW ACTIVE PHASE SHIFTER

Fig. 1 shows a new scheme of an active phase shifter using a vector sum method. The conceptual design of the phase shifter is shown in Fig. 1(a). The numbers in parentheses indicate the magnitudes of the RF signals, and a, b, A, B are variable gains of the VGAs, respectively. Fig. 1(b) and (c) show the vector diagram illustrating the magnitudes and the phases of the RF signals of the corresponding paths.

As shown in Fig. 1(a), the first stage VGAs are excited with the same phase and magnitude through the in-phase power divider at a designated RF frequency. The outputs of the first stage VGAs are then combined through a 3dB quadrature hybrid coupler to produce RF signals 1, 2 as shown in Fig. 1(b). RF signal $2'$ is obtained by shifting the phase of RF signal 2 by 180^o. The second stage VGAs are then excited by the RF signal 1, $2'$ as shown in Fig. 1(a). The outputs of the second stage VGAs are combined through an in-phase power combiner. Finally, a phase and magnitude controlled RF signal 'output' can be obtained as shown in Fig. 1(c).

'output' can be thought of as the sum of four RF signals on the axes, that is, Aa, Ab, Ba, Bb as shown in Fig. 1(c). If each quadrant is considered as the variable gains of the four VGAs as shown in parentheses of Fig. 1(c), the four RF signals on the axes can then be obtained by the multiplication of the gains corresponding to the adjacent quadrants of each axis. The phase and magnitude of the RF signal 'output' can also be controlled, and Fig. 2(a) shows how to control the gains of the four VGAs to achieve a constant magnitude and a variable phase shift; there is only one zero-gain VGA out of four VGAs in any phase state of the output signal except $0^o, 90^o, 180^o, 270^o$ as shown in Fig. 2(a), and the multiplication of gains as mentioned. These points make the new active phase shifter to be more efficient than any other schemes in power and gain. In addition, there are only four passive circuits as shown in Fig. 1(a), which leads the circuit to smaller size and lower loss.

III. A UNIQUE DIGITAL PHASE CONTROL METHOD

There are some restrictions for a VGA in implementing and operating the new active phase shifter. One of restrictive factors is, for example, the impedence matching between VGAs and other passive circuits. Another one may be invariance of the transmission phase of a VGA at different gain states of a VGA. To alleviate these restrictions, the unique digital operation of the phase shifter is suggested in this paper. This reduces the number of gain states to lighten the restrictions, therefore, the total number of restrictions is down. Fig. 2(b) shows the phase states of a 3-bit digital phase shifter, and Fig. 2(a) shows the gain states of VGAs corresponding to the phase states. From Fig. 2(a) one can find that at least three phase states are necessary for the 3-bit phase control. However, the three gain states of four VGAs are too many for 8 phase states, because the combination of three gain states of four VGAs is 81.

Assuming that the 8 phase states can be achieved by combining only two gain states of four VGAs, then there are three cases between the gains of each stage VGAs; one is higher or lower than the other, or both are equal. So the total number of the combination of the gain states is 9, as shown in Table 1. Here, x and y are the magnitudes of the signal corresponding to $x-$ and $y-$ axis in Fig. 1(c), i.e., $x = Ab - Ba,\ y = Aa - Bb$. From Table I, one can find that the 3-bit phase control is possible through only two gain states. For the constant magnitude of the output signal, as one can see from Table II, at least one of the following two equations must have one root.

$$M^2(1-k)\sqrt{2} = M^2(1-k^2), \quad (0 < k < 1) \qquad (1)$$

$$M^2(1-k)\sqrt{2} = kM^2(1-k^2), \quad (0 < k < 1) \qquad (2)$$

Only one solution of $k = \sqrt{2} - 1$ can be obtained from Eq.(1). So the 3-bit phase control can be achieved through combining the two gain states of four VGAs with 7.66dB ($-20\ log(\sqrt{2} - 1)$) gain difference. The gains of the VGAs for various phases of the output signal are shown in Table II. The recurrence of the smaller gain state rotates in Table II can be explained by the two vector diagrams in Fig. 3. Each vector diagram shows the mechanism of -45^o and 0^o phase shifts, respectively. The 3-bit phase control can be done by rotating these two states with 90^o step, and to do so, the smaller gain state has to rotate. Now, as shown in Table II, the VGAs with gain A, a, B, b are defined as VGA1, VGA2, VGA3 and VGA4, respectively, and one can define the control states of VGAs for the various phase states as the bottom row of Table II.

As shown in Fig. 3, there is 1.6dB ($20\ log(1 - k^2)$) loss compared with the analog phase control as shown in Fig. 2(a). In addition, each VGA has only two gain states, but three gain states can be found on the axes of the vector diagrams. This is because of the multiplication of gains. Therefore, the suggested digital phase control in this paper is the unique method of the proposed scheme of the active phase shifter.

IV. IMPLEMENTATION AND RESULTS

The new active phase shifter was designed and implemented on microstrip for the frequency range 2.2~2.3 GHz using packeged DGFETs for VGAs. Fig. 4 shows the microstrip pattern of the designed circuit. Wilkinson power combiners were used as the in-phase power combiner/divider, a 3 dB quadrature hybrid coupler was realized with a branch line hybrid coupler, and a 180^o phase shifter was realized with a delay line.

The measured and the estimated phase shifts of the circuit at a center frequency for various control states are plotted in Fig. 5. The phase difference between the measured and the estimated ones is within $\pm 7^o$. The performance of a VGA is shown in Fig. 6(a). As mentioned in Section III, the gain difference between the higher and the lower gain states is nearly 7.6dB at a center freauency, and the phase difference is 6^o.

Fig. 6(b) shows the overall gain of the circuit for various control states. Note that the average overall gain is 11.5dB with a gain variation ±0.5dB and the gain of the higher gain state is about 11.5dB as shown in Fig. 6(a). This shows that the new active phase shifter is more efficient than any other active phase shifters using a vector sum method [4][5].

V. CONCLUSION

A new active phase shifter using a vector sum method is proposed together with an unique digital phase control method of the circuit. It is also shown that the circuit is more efficient than any other active phase shifters using a vector sum method. The circuit was designed, implemented and achieved by the 3-bit digital phase shift with 11.5dB gain. The phase and gain variations of the circuit are within $\pm 7^o$ and ±0.5dB, respectively.

This circuit can be applied to the phased array antenna systems in the form of merging an amplifier and a phase shifter. And inherently the proposed active phase shifter can control the magnitude and phase of a RF signal continuously, so it is more adequate for the adaptive array antenna systems.

REFERENCES

[1] C. Tsironis and P. Harrop, "Dual-Gate GaAs MESFET Phase Shifter with Gain at 12GHz", *Electronics Letters*, Vol. 16, No. 14, July 1980, pp. 553–554

[2] M. Kumar and H. C. Huang, "Dual Gate MESFET variable-gain, constant-output power amplifier", *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-29, 1981, pp. 185–189

[3] M. Kumar, R. J. Menna and H. Huang, "Broad-Band Active Phase Shifters Using Dual Gate MESFET", *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-29, 1981, pp. 1098–1101

[4] Y. Gazit and H. C. Johnson, "A continuously-variable Ku-band phase/amplitude module", *IEEE MTT-S Int. Microwave Symp. Dig.*, 1981, pp. 436–438

[5] John R. Selin, "Continuously Variable L-Band Monolithic GaAs Phase Shifter", *Microwave J.*, Vol. 30, September 1987, pp. 211–218

[6] D. K. Paul and P. Gardner, "Microwave Quadrature Active Phase Shifter using MESFETs", *Microwave and Optical Tech. Lett.*, Vol. 15, 1997, pp. 359–360

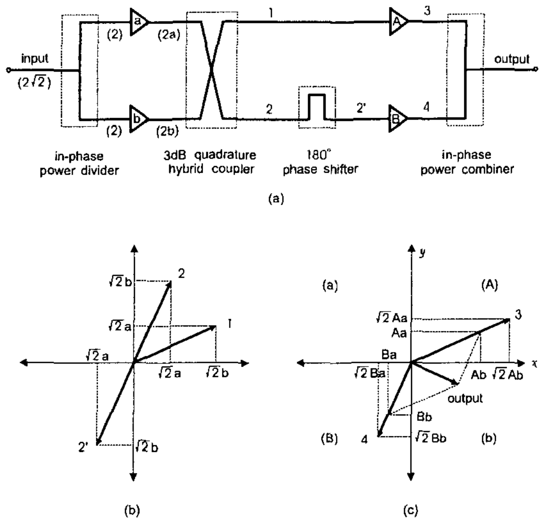


Fig. 1. (a) The schemetic diagram of a new active phase shifter and (b),(c) Vector diagrams

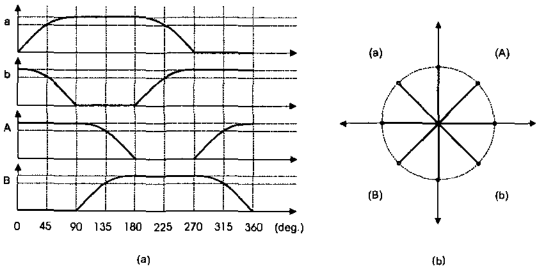


Fig. 2. (a) The phase shift of the output vs. each gains of VGAs (linear scale) (b) Vector diagram for a 3-bit phase shifter operation

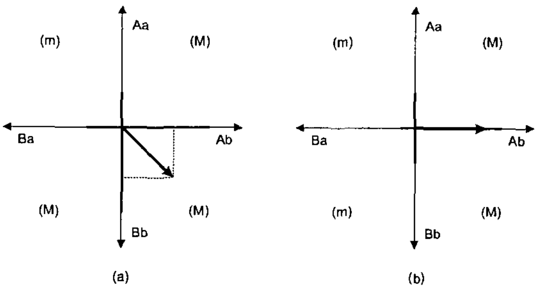


Fig. 3. Vector diagrams for (a)-45^o and (b)0^o

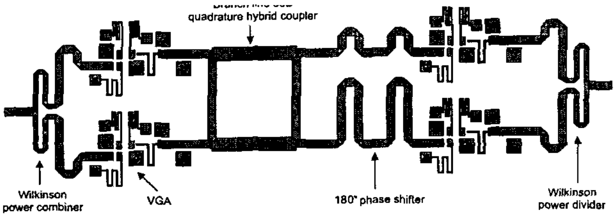


Fig. 4. The microstrip pattern of the proposed active phase shifter

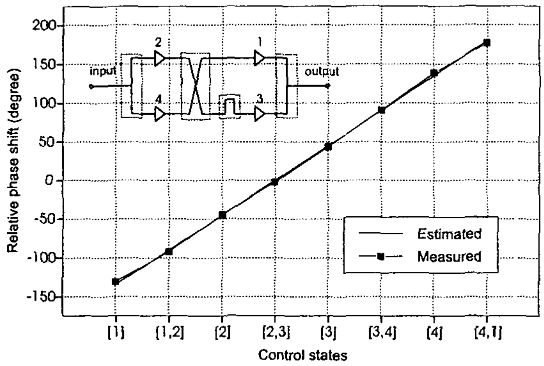
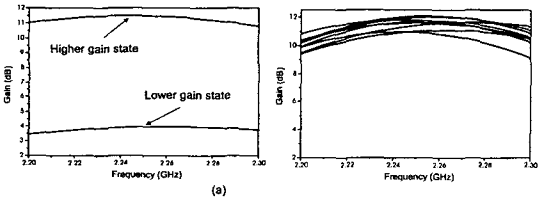


Fig. 5. The relative phase shift vs. control states of VGAs at a center frequency



(a)

Fig. 6. (a) Measured gains of both gain states of VGAs (b) The measured gain of the new active phase shifter for various control states

TABLE I

THE PHASE AND MAGNITUDE OF THE OUTPUT SIGNAL FOR NINE GAIN STATES

		$A = B$ $(M \text{ or } kM)$	$A = kB$ $B = M$	$B = kA$ $A = M$
$a = b$ $(M \text{ or } kM)$	x	$Aa - Aa = 0$	$aB(k-1)$	$aA(1-k)$
	y	$Aa - Aa = 0$	$aB(k-1)$	$aA(1-k)$
	Phase	No Output	-135^o	45^o
	Magnitude	0	$aB(1-k)\sqrt{2}$ $aB = (M^2 \text{ or } kM^2)$	$aA(1-k)\sqrt{2}$ $aA = (M^2 \text{ or } kM^2)$
$a = kb$ $b = M$	x	$bA(1-k)$	$bB(k-k) = 0$	$bA(1-k^2)$
	y	$bA(k-1)$	$bB(k^2-1)$	$bA(k-k) = 0$
	Phase	-45^o	-90^o	0^o
	Magnitude	$bA(1-k)\sqrt{2}$ $bA = (M^2 \text{ or } kM^2)$	$M^2(1-k^2)$	$M^2(1-k^2)$
$b = ka$ $a = M$	x	$aA(k-1)$	$aB(k^2-1)$	$aA(k-k) = 0$
	y	$aA(1-k)$	$aB(k-k) = 0$	$aA(1-k^2)$
	Phase	135^o	-180^o	90^o
	Magnitude	$aA(1-k)\sqrt{2}$ $aA = (M^2 \text{ or } kM^2)$	$M^2(1-k^2)$	$M^2(1-k^2)$

$(0 < k < 1)$

TABLE II

GAIN STATES OF VGAS FOR THE VARIOUS PHASES OF THE OUTPUT SIGNAL

	-135^o	-90^o	-45^o	0^o	45^o	90^o	135^o	180^o	
A	m	m	M	M	M	M	M	m	VGA1
a	M	m	m	m	M	M	M	M	VGA2
B	M	M	M	m	m	m	M	M	VGA3
b	M	M	M	M	M	m	m	m	VGA4
	[1]	[1,2]	[2]	[2,3]	[3]	[3,4]	[4]	[4,1]	

$m = (\sqrt{2} - 1)M$