

A New Active Phase Shifter Using a Vector Sum Method

S. J. Kim and N. H. Myung

Abstract—In this letter, 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 3 dB quadrature hybrid coupler and variable gain amplifiers (VGA's) using dual gate FET's (DGFET's). Furthermore, it is also shown that the proposed scheme is more efficient and works properly with the digital phase control method.

Index Terms—Active phase shifter, variable gain amplifier.

I. INTRODUCTION

THERE are two kinds of active phase shifters. One is controlling 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]–[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, variable gain amplifiers (VGA's) are often realized using DGFET's. Recently a quadrature active phase shifter using single gate FET's 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 VGA's. In this letter, 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 VGA's, respectively. Fig. 1(b) and (c) shows the vector diagram illustrating the magnitudes and the phases of the RF signals of the corresponding paths.

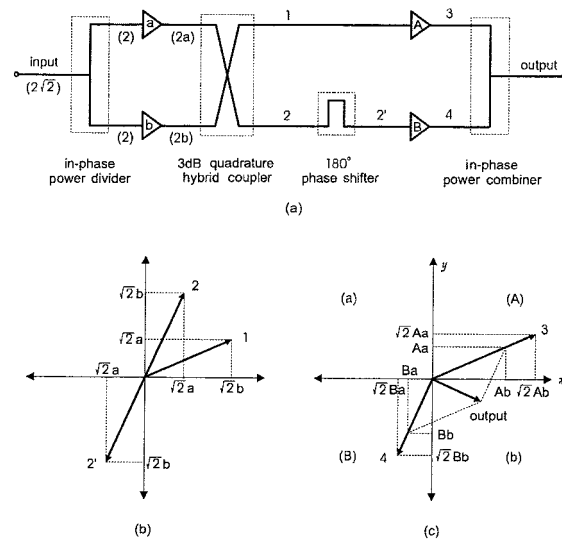


Fig. 1. (a) Schematic diagram of a new active phase shifter and (b),(c) Vector diagrams.

As shown in Fig. 1(a), the first stage VGA's 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 VGA's are then combined through a 3 dB 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° . The second stage VGA's are then excited by the RF signal 1, 2', as shown in Fig. 1(a). The outputs of the second stage VGA's 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 VGA's 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 VGA's to achieve a constant magnitude and a variable phase shift; there is only one zero-gain VGA out of four VGA's in any phase state of the output signal except 0° , 90° , 180° , and 270° , 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.

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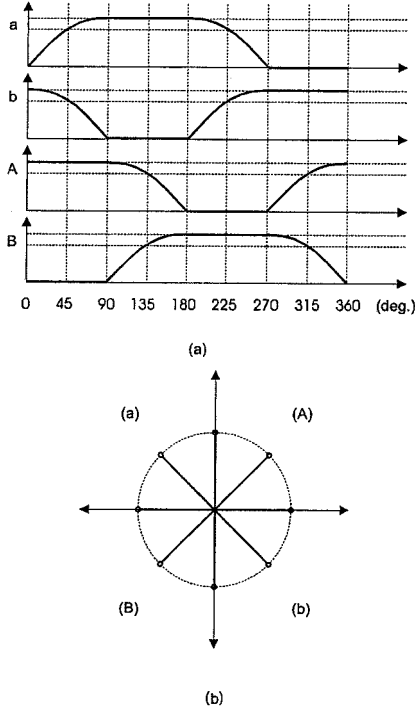


Fig. 2. (a) Phase shift of the output versus each gains of VGA's (linear scale) and (b) vector diagram for a 3-bit phase shifter operation.

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 impedance matching between VGA's 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 letter. 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 VGA's 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 VGA's are too many for eight phase states, because the combination of three gain states of four VGA's is 81.

Assuming that the eight phase states can be achieved by combining only two gain states of four VGA's, then there are three cases between the gains of each stage VGA's; one is higher or lower than the other, or both are equal. So the total number of the combination of the gain states is nine, as shown in Table I. 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.

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

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

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

		$A = B$ (M or kM)	$A = kB$ $B = M$	$B = kA$ $A = M$
$a = b$ (M 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°	45°
$a = kb$ $b = M$	Magnitude	0	$aB(1-k)\sqrt{2}$ $aB = (M^2 \text{ or } kM^2)$	$aA(1-k)\sqrt{2}$ $aA = (M^2 \text{ or } kM^2)$
	x	$bA(1-k)$	$bB(k-k) = 0$	$bA(1-k^2)$
	y	$bA(k-1)$	$bB(k^2-1)$	$bA(k-k) = 0$
$b = ka$ $a = M$	Phase	-45°	-90°	0°
	Magnitude	$bA(1-k)\sqrt{2}$ $bA = (M^2 \text{ or } kM^2)$	$M^2(1-k^2)$	$M^2(1-k^2)$
	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°	-180°	90°
	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°	-90°	-45°	0°	45°	90°	135°	180°	
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]	

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

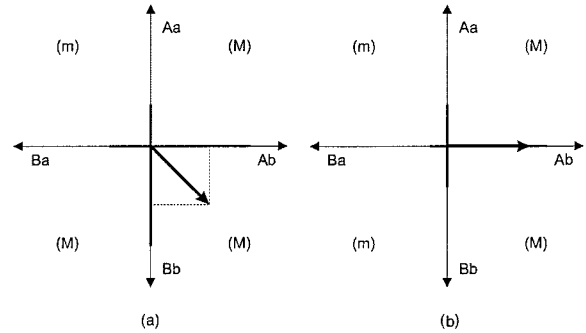


Fig. 3. Vector diagrams for; (a) -45° and (b) 0° .

Only one solution of $k = \sqrt{2} - 1$ can be obtained from (1). So the 3-bit phase control can be achieved through combining the two gain states of four VGA's with 7.66 dB ($-20 \log(\sqrt{2} - 1)$) gain difference. The gains of the VGA's 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° and 0° phase shifts, respectively. The 3-bit phase control can be done by rotating these two states with 90° step, and to do so, the smaller gain state has to rotate. Now, as shown in Table II, the VGA's with gain A, a, B, b are defined as VGA1, VGA2, VGA3, and VGA4, respectively, and one can define the control states of VGA's for the various phase states as the bottom row of Table II.

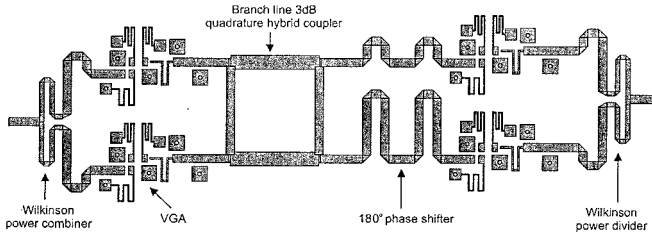


Fig. 4. Microstrip pattern of the proposed active phase shifter.

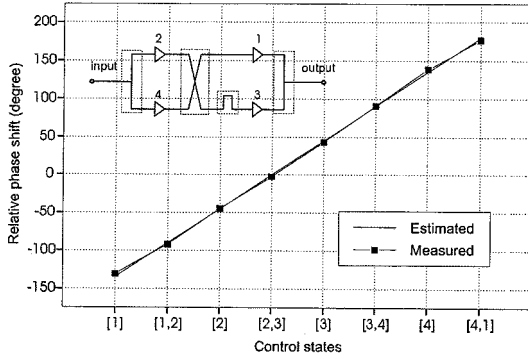


Fig. 5. Relative phase shift versus control states of VGA's at a center frequency.

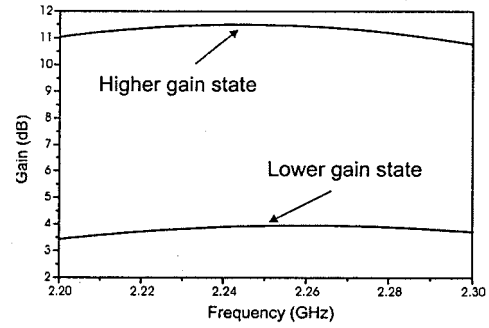
As shown in Fig. 3, there is 1.6 dB ($20 \log(1 - k^2)$) loss compared with the analog phase control as shown in Fig. 2(a). In addition, each VGA has only two gain states, but three gain states can be found on the axes of the vector diagrams. This is because of the multiplication of gains. Therefore,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

IV. IMPLEMENTATION AND RESULTS

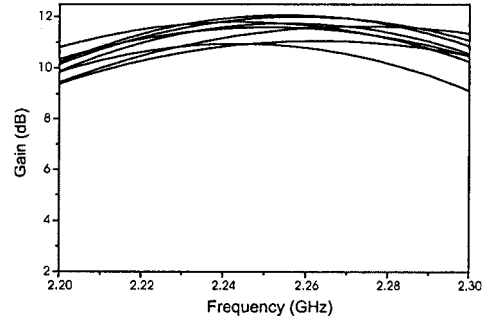
The new active phase shifter was designed and implemented on microstrip for the frequency range 2.2~2.3 GHz using packaged DGFET's for VGA's. Fig. 4 shows the microstrip pattern of the designed circuit. Wilkinson power combiners were used as the in-phase power combiner/divider, a 3 dB quadrature hybrid coupler was realized with a branch line hybrid coupler, and a 180° 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 $\pm 7^\circ$. 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 7.6 dB at a center frequency, and the phase difference is 6° .

Fig. 6(b) shows the overall gain of the circuit for various control states. Note that the average overall gain is 11.5 dB with a gain variation ± 0.5 dB and the gain of the higher gain state is about 11.5 dB 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].



(a)



(b)

Fig. 6. (a) Measured gains of both gain states of VGA's and (b) the measured gain of the new active phase shifter for various control states.

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 11.5 dB gain. The phase and gain variations of the circuit are within $\pm 7^\circ$ and ± 0.5 dB, 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.

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