A New Active RF Phase Shifter Using Variable Gain, Drain Voltage Controlled PHEMTs: A 2.4-GHz ISM Implementation

Stelios A. Mitilineos, *Student Member, IEEE*, George K. Mitropoulos, and Christos N. Capsalis

***Abstract*—Phase shifters operating at RF bands are an essential component of phased and adaptive arrays circuits. In this letter, an active phase shifter is proposed, using vector summing of an in-phase and a quad-phase replica of the incoming signal. The proposed scheme was designed and implemented using a Wilkinson power combiner/divider, a branch line hybrid coupler and single-stage variable gain amplifiers (VGAs), achieving continuous phase shift within the range of [0°, 90°]. The manufactured prototype is suitable for WLAN operations in the 2.4-GHz ISM band. Details of the phase shifter design and experimental results are presented.**

***Index Terms*—Vector summing, voltage controlled amplifier, voltage controlled phase shifter.**

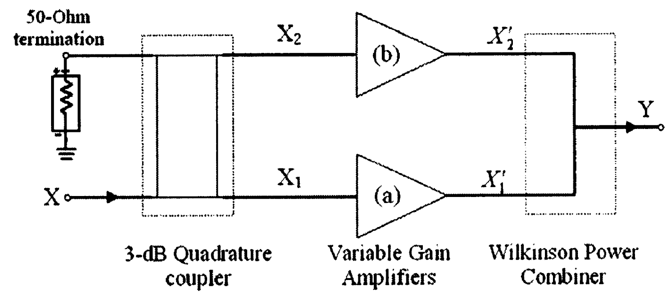

Fig. 1. Schematic diagram of the phase shifter and output signals illustration.

I. Introduction

ANTENNA arrays and smart antennas have been suggested to satisfy the demand for increased data rates and overcome the lack of unlimited channel bandwidth. In the case where the signal is down-converted and the beam forming process is accomplished in the IF band, a large number of down-converters is required, leading to high cost solutions. Furthermore, in many cases the initial phase of the signal is lost during the down-conversion process. Consequently, evolution of RF phase shifters is very important for cost-effective adaptive components.

In the literature, several approaches, regarding the design of phase shifters, are met. Phase shift is conventionally achieved by dielectric and ferrite components, as in [1]–[3]. Transmission lines and customized switching layouts are used in digital phase shifters implementations. All-pass filters are also used for phase shifting, where a variable resistor, capacitor or inductor alters the phase of the transmission coefficient while the gain remains constant [4], [5].

Control of the gate voltage bias of field effect transistors (FETs) is an alternative technique for continuous phase shifting. An extensive study of the phase shifts in single- and dual- gate MESFETs, when varying the gate bias voltage, can be found in [6] and analogous results for multichannel heterojunction FETs are presented in [7].

In this letter, a new active phase shifter, printed on a PC board, suitable for WLAN applications, is designed and implemented. The phase shift is controlled through the application of variable drain bias voltage on pseudomorphic high electron mobility transistors (PHEMTs). The proposed prototype active phase shifter overcomes the problems of inefficiency which arise in the case of gate voltage controlled phase shifters [8]. Design considerations and measurements results of the implemented prototype phase shifter are presented.

II. Proposed Active Phase Shifter

The concept of the implemented technique is illustrated in Fig. 1. The variable gain amplifiers (VGAs), namely (a) and (b), are excited by the same magnitude but 90° phase difference RF signals, X_1 and X_2, through a 3 dB quadrature hybrid coupler. Variable gain amplifiers' gain is controlled via their bias drain voltages, while their respective gate voltages remain constant. The outputs of the VGAs, X'_1 and X'_2, are then combined through an in-phase Wilkinson combiner to provide a phase controlled output RF signal. Let the input signal be

$$X = |X| \exp(j\phi). \quad (1)$$

The outputs of the coupler are then given by

$$X_1 = |X| \exp[j(\phi + \theta_1)] \quad (2a)$$

$$X_2 = |X| \exp[j(\phi + \theta_1 + 90°)] \quad (2b)$$

where θ_1 is the phase shift due to the branch coupler.

In the case where the VGAs exhibit variable gain but constant phase shift (implemented case), the output signals of the amplifiers are given by

$$X'_1 = A|X| \exp[j(\phi + \theta_3)] \quad (3a)$$

$$X'_2 = B|X| \exp[j(\phi + \theta_3 + 90°)] \quad (3b)$$

Manuscript received December 13, 2004; revised March 29, 2005. The review of this letter was arranged by Associate Editor J.-G. Ma.

S. A. Mitilineos is with the Laboratory of Antennas, Wireless and Long Range Communications, ECE, National Technical University of Athens, Athens, Greece (e-mail: smitil@mail.ntua.gr).

G. K. Mitropoulos is with the Laboratory of Microwave and Fiber Optics, ECE, National Technical University of Athens, Athens, Greece (e-mail: gmitr@esd.ece.ntua.gr).

C. N. Capsalis is with the Laboratory of Antennas, Wireless and Long Range Communications, ECE, National Technical University of Athens, Athens, Greece (e-mail: ccaps@central.ntua.gr).

Digital Object Identifier 10.1109/LMWC.2005.851555

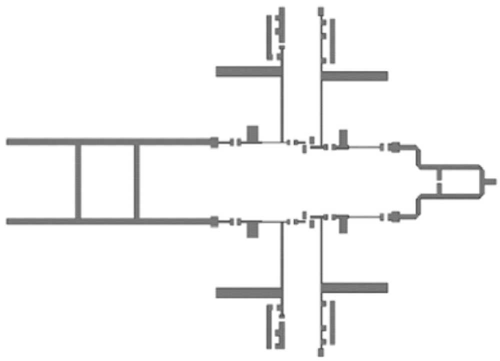

Fig. 2. Microstrip layout of the manufactured active phase shifter.

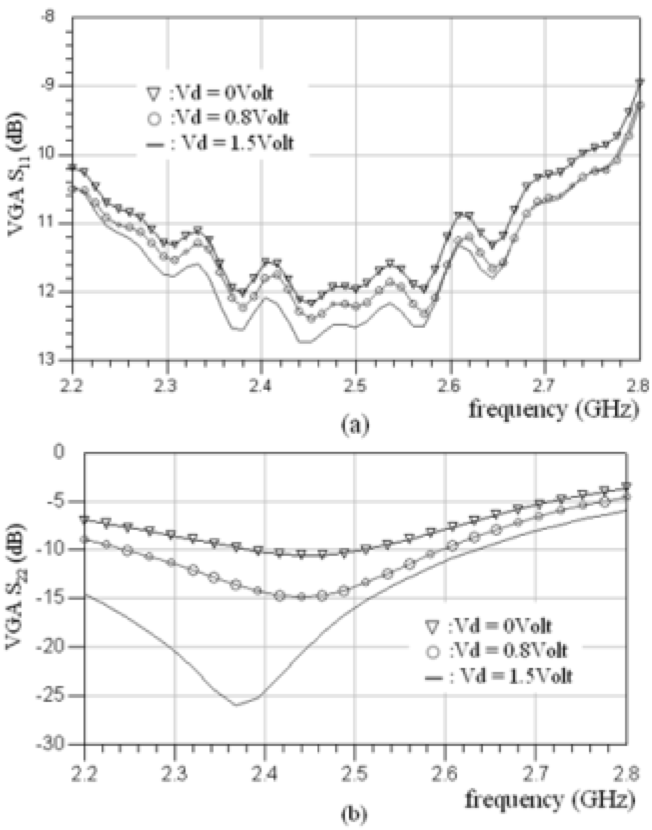

Fig. 3. VGA's measured reflection coefficients, in dB: (a) input reflection coefficient and (b) output reflection coefficient.

where $\theta_3 = \theta_1 + \theta_2, \theta_2$ being the phase shift introduced by the amplifiers, and A, B correspond to the gain of amplifiers (a) and (b), respectively. The output signals of the amplifiers are given by

$$Y = |X|(A + jB)\exp[j(\phi + \theta_5)] \tag{4}$$

where $\theta_5 = \theta_3 + \theta_4$, and θ_4 represents the phase shift due to the combiner. The total phase shift is given by

$$\theta = \tan^{-1}\left(\frac{B}{A}\right) + \theta_5. \tag{5}$$

Angle θ_5 may be used as phase shift bias and, if requested, a zero bias is easily implemented using a transmission line. From (5), it is shown that continuous phase shift is achieved, adjusting only VGAs' gains.

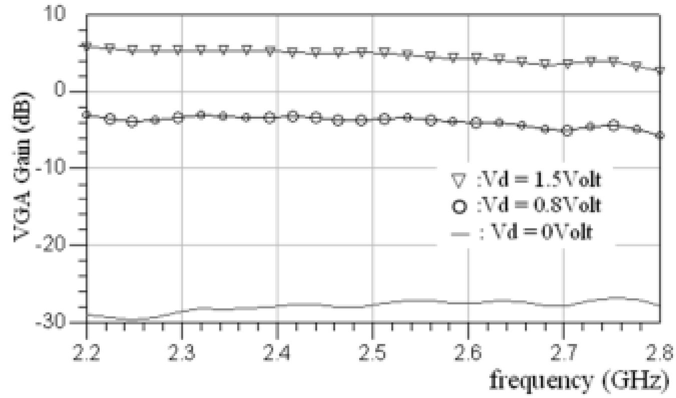

Fig. 4. VGA's measured gain (S21, in dB), for various bias drain voltages.

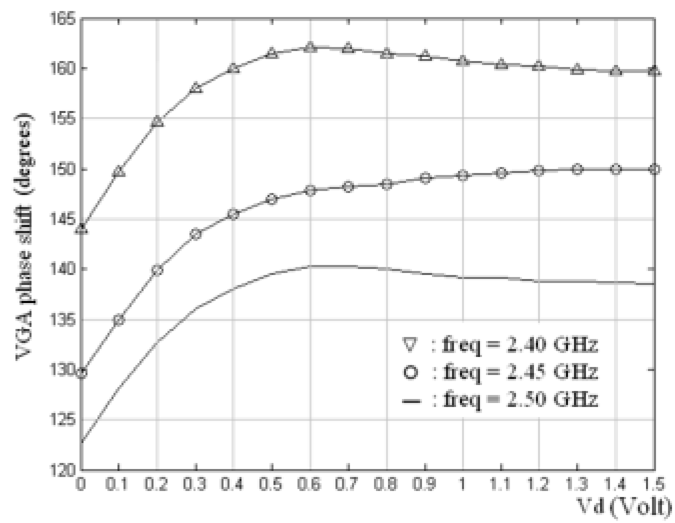

Fig. 5. VGA's measured phase shift versus bias drain voltage, for various frequencies.

III. Implementation and Measurement Results

The active phase shifter is designed and implemented for the 802.11b/g WLAN frequency range using packaged PHEMTs for VGAs. A printed circuit board is implemented over FR4 substrate, having a thickness of $d = 1.6$ mm and relative dielectric permittivity of approximately 4.5, at frequencies around 2.45 GHz. In Fig. 2, the microstrip layout of the manufactured active phase shifter is depicted.

The packaged PHEMT transistors ATF-38 143 [9], by Agilent, are used as the single stage variable gain amplifiers, through which variable gain but constant phase shift is achieved within the entire gain range. The applied gate voltage, V_g, was set equal to 0.3 V, while the drain voltage, V_d, was varied within the range of 0–1.5 V.

A VGA was manufactured separately and additionally to the overall phase shifter, in order to demonstrate the functionality of the active components. The measured performance of the VGA is depicted in Figs. 3–5. The input and output reflection coefficients are kept below -10 dB, for all applied bias drain voltages in the frequency range between 2.4 and 2.5 GHz. The gain difference between the higher and the lower gain states is approximately 35 dB while the phase difference is below 8°, for $V_d > V_{g,\mathrm{bias}}$ (=0.3 V).

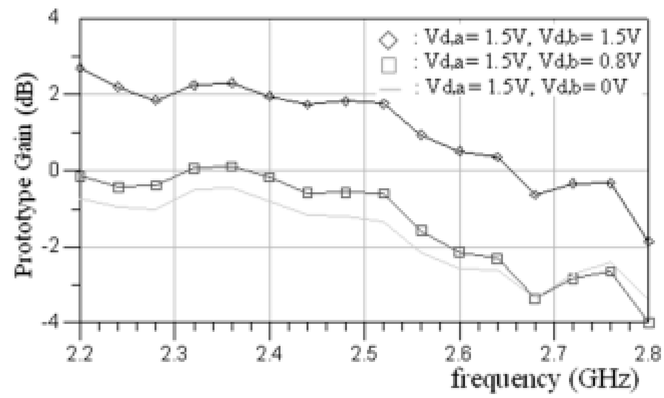

Fig. 6. Manufactured phase shifter overall gain (S21, in dB).

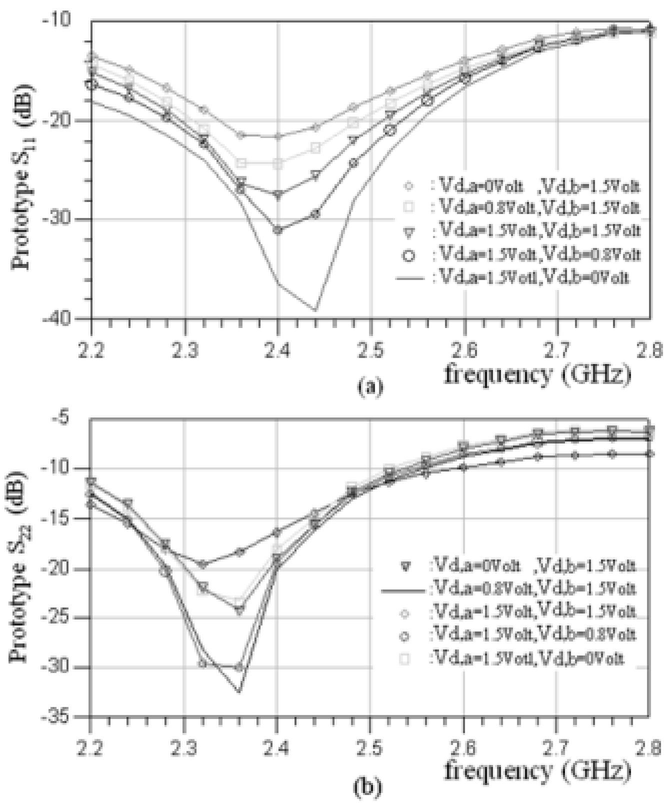

Fig. 7. Manufactured phase shifter overall reflection coefficients, in dB: (a) input reflection coefficient and (b) output reflection coefficient.

The overall gain of the manufactured prototype phase shifter is depicted in Fig. 6. The drain voltages $V_{d,a}$ and $V_{d,b}$ correspond to the amplifiers A and B, respectively. The mean overall gain is approximately 2 dB, with a gain variation of less than 3 dB versus $V_{d,b}$. In Fig. 7, overall reflection coefficients of the manufactured phase shifter are illustrated, while, in Fig. 8, the overall phase shift versus the applied bias drain voltages is shown. Note that the accomplished overall phase shift is more than 90°, in the specified frequency range of 2.4–2.5 GHz, while the achieved operational bandwidth is more than 200 MHz.

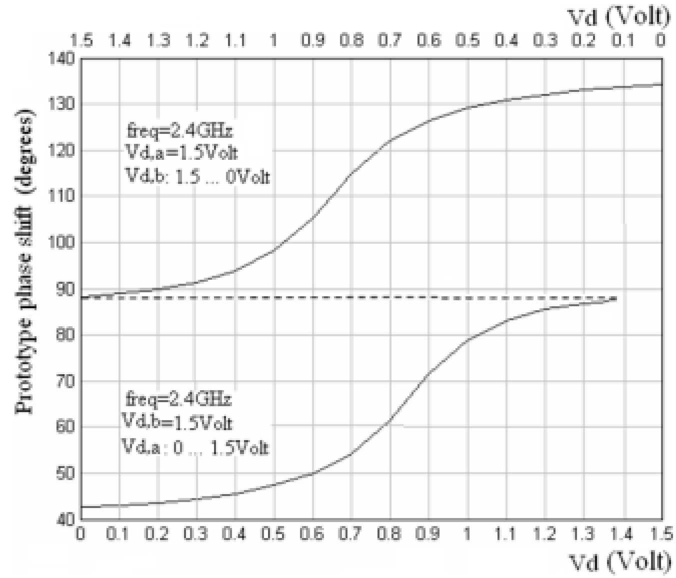

Fig. 8. Manufactured prototype overall phase shift versus drain voltages, at the frequency of 2.4 GHz.

IV. Conclusion

A novel technique for RF voltage controlled phase shifters and a prototype implementation suitable for ISM applications are presented. The proposed active circuit can be applied to phased antenna arrays systems but also inherently control the phase of the RF signal in a continuous sense.

References

[1] S. Bolioli, H. Benzina, H. Baudrand, and B. Chan, "Centimeter-wave microstrip phase shifter on a ferrite-dielectric substrate," *IEEE Trans. Microwave Theory Tech.*, vol. 37, no. 4, pp. 698–705, Apr. 1989.

[2] R. Andriamanjato, B. Chan, J. W. Tao, and H. Baudrand, "Full-wave analysis of dielectric waveguide ferrite phase shifter with longitudinal magnetization," *Electron. Lett.*, vol. 28, no. 20, pp. 1907–1908, Sep. 24, 1992.

[3] V. V. Meriakri and M. P. Parkhomenko, "Millimeter wave phase shifters based on ferrite dielectric waveguides," in *Proc. 12th Int. Conf. Microwaves Radar*, vol. 2, May 1998.

[4] H. Hayashi and M. Muraguchi, "An MMIC active phase shifter using a variable resonant circuit," in *IEEE MTT-S Int. Dig.*, vol. 3, Jun. 1998, pp. 1573–1576.

[5] D. Viveiros Jr., D. Consonni, and K. A. Jastrzebski, "A tunable all-pass MMIC active phase shifter," *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 8, pp. 1885–1889, Aug. 2002.

[6] J. P. Mondal, A. G. Milnes, J. G. Oakes, and S. K. Wang, "Phase shifts in single- and dual-gate GaAs MESFETs for 2–4 GHz quadrature phase shifters," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-32, no. 10, pp. 1280–1288, Oct. 1984.

[7] M. Nawaz and G. U. Jensen, "Design of active phase shifters based on multichannel heterojunction field effect transistors (MCHFETs)," *IEEE Trans. Electron Devices*, vol. 43, no. 11, pp. 1788–1798, Nov. 1996.

[8] S. J. Kim and N. H. Myung, "A new active phase shifter using a vector sum method," *IEEE Microw. Guided Wave Lett.*, vol. 10, no. 6, pp. 233–235, Jun. 2000.

[9] *Low Noise Pseudomorphic HEMT in a Surface Mount Plastic Package*, ATF-38 143 Technical Data, Agilent Technologies, 2005.