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CMOS VGA and Ku-Band Phase Shifter for High Performance RF and Microwave Applications

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ABSTRACT –

Abstract-The two blocks that are covered are the low-power 7.4-mW CMOS Variable Gain Amplifier operating at 22.7–29.7 GHz and the half-quadrant control-based 6-Bit Vector-Sum Phase Shifter operating at a Ku-Band. The CMOS VGA features a wide gain range for tuning, from -4.5 dB up to 19.2 dB, resulting in an aggregate span of 23.7 dB with an average noise figure of 3.26 dB. Such capabilities make it exceptionally suitable for high-frequency communication and radar systems demanding efficient power with very accurate gain control for good signal quality under all possible conditions. The Ku-Band Phase Shifter with 6-bit resolution and half-quadrant control allows 64 discrete phase steps, thereby allowing fine-tuning up to 12–18 GHz. In the case of phased array antennas and radars, accurate beam steering and phase alignment significantly influence the performance of the system. Aside from this, the half-quadrant control contributes to better phase coherence so that maximum signal directionality and stability can be acquired. The paper is in such high-performance VGA and phase shifter designs and stresses the impact of these innovations towards improving adaptability and performance in RF and microwave systems. This work underscores the significance of gain and phase control in developing efficient high-frequency signal processing solutions.

1.Introduction

Precise control over signal amplitude and phase at high frequencies is paramount in the rapidly advancing fields of communication systems, radar technology, and phased-array antennas. Variable gain amplifiers (VGAs) and phase shifters are crucial components in achieving such control, allowing systems to adapt dynamically to changing conditions and maintain optimal performance. Two advanced designs are presented in this paper—a 7.4-mW CMOS VGA with a broad gain tuning range from 19.2 to -4.5 dB operating at 22.7–29.7 GHz and a Ku-Band 6-Bit Vector-Sum Phase Shifter with half-quadrant control. The first design is a low-power, high-frequency CMOS VGA, specifically designed to operate at 22.7–29.7 GHz with a wide 23.7 dB gain tuning range. This VGA also achieves an average noise figure of 3.26 dB, making it ideal for applications requiring efficient power usage and robust gain control at millimeter-wave frequencies. Such VGAs are prominent in signal processing in the areas of communication and radar systems as they provide fine adjustment in gain in accordance with the fluctuating conditions of signal strength and noise. The second design is a Ku-Band 6-Bit Vector-Sum Phase Shifter with phase modulation up to half-quadrant, suitable for frequencies typically found within the Ku-Band (12–18 GHz). It features 6-bit resolution for 64 different phase states, making it suitable for high-precision control over signal phase. This precision is vital in phased-array antennas and in advanced radar applications, as accuracy in beam steering and phase alignment has a direct influence on performance. The half-quadrant control method increases phase control resolution, leading to better signal coherency and optimal directional control. Together, these designs highlight the innovative approaches used to enhance signal control in high-frequency systems. This paper will explore the design principles, operational advantages, and applications of both the CMOS VGA and the Ku-Band Vector-Sum Phase Shifter, emphasizing their roles in advancing the performance and adaptability of modern RF and microwave systems.

2.System model

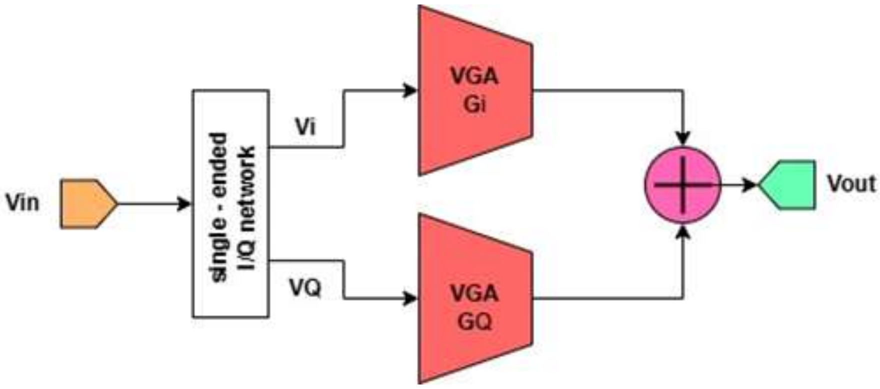

Fig.2.1 Block diagram of the proposed 6-bit vector-sum phase shifter

The input signal, $\boldsymbol{v_{in}}$, is typically a single-ended RF or microwave signal that requires amplification and processing. This signal is first passed through a single-ended IQ network, which splits it into two orthogonal components, $\boldsymbol{v_i}$ and $\boldsymbol{v_Q}$, corresponding to the In-phase (I) and Quadrature-phase (Q) signals. IQ separation is a critical process in many RF systems as it enables phase and amplitude modulation while enhancing signal processing capabilities. The system includes two Variable Gain Amplifiers (VGAs), labeled VGA(G_i) and VGA(G_Q) which independently amplify the I and Q signals. The gain of each amplifier can be adjusted to achieve the desired amplitudes for each signal component, making it suitable for applications where adjustable signal levels or phase adjustments are necessary. After amplification, the I and Q signals are combined using a combiner. This process involves summing the two components with specific phase shifts to produce the desired output signal. The final output signal $\boldsymbol{v_{out}}$, is generated after the combination of the I and Q components. By controlling the VGA gains, the system's gain and phase can be precisely managed, enabling its use in applications such as phase modulation, amplitude modulation, and signal conditioning. I/Q phase-shifting networks are commonly utilized within RF systems to split a signal into two components shifted 90 degrees out of phase. These networks include resistors, capacitors, and inductors that work together to achieve this functionality. Resistors, such as R1, R2, and R3, play a role in the impedance network, determining the output signals' phase and amplitude while regulating the current through the circuit. Capacitors, like C1, C2, C3, and C4, introduce phase shifts in the signal based on their capacitance values and the input signal frequency, enabling precise control of the phase. Inductors, L1 and L2, complement the capacitors, further refining the phase shift and providing a filtering effect to achieve the required 90-degree phase difference between outputs. The circuit operates as an all-pass network, dividing the input signal into two distinct paths. The signal passing through the upper path, composed of R2, L1, C1, and C2, retains its phase characteristics, while the signal in the lower path, which traverses R3, L2, C3, and C4, is shifted by 90 degrees relative to the upper path. This configuration generates quadrature outputs, with one signal representing the in-phase (I) component and the other the quadrature-phase (Q) component. Such networks are fundamental in RF and communication systems, supporting applications like quadrature modulation and demodulation in QPSK and QAM systems, where signals with a 90-degree phase shift are used to encode data. They are also instrumental in frequency mixing for radio receivers, facilitating the

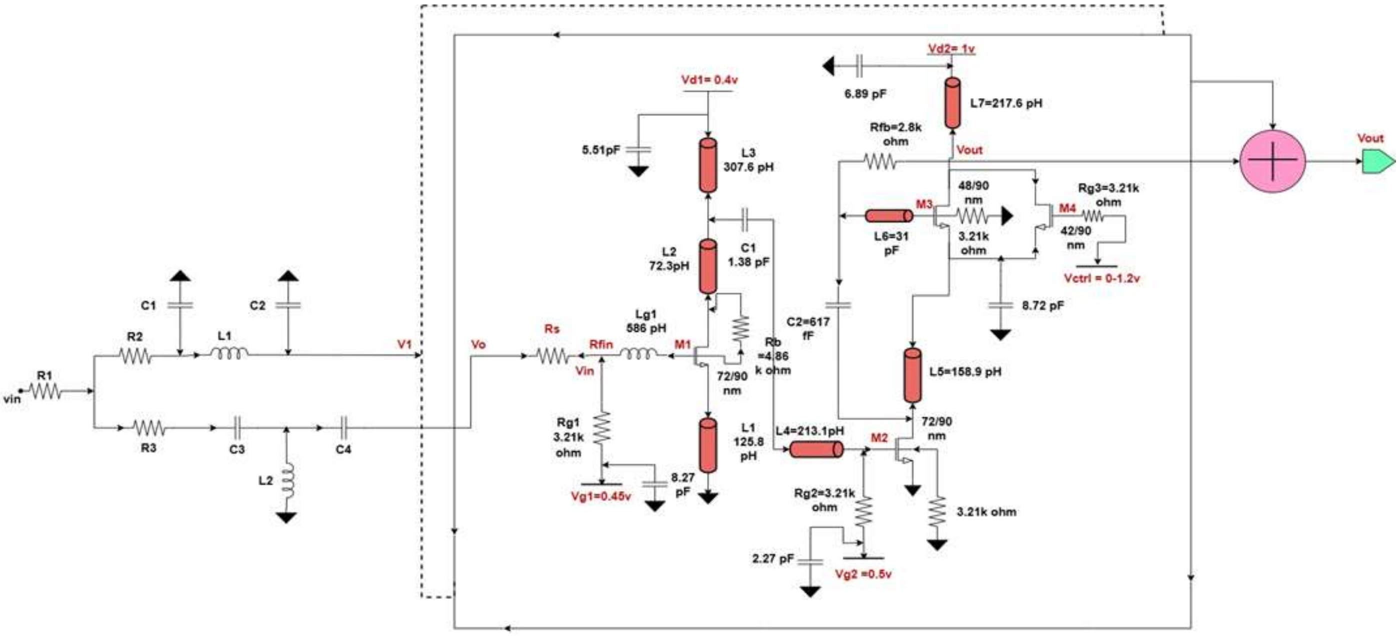

Fig.2.2 The full schematic of the proposed vector-sum phase shifter

conversion of signals to different frequencies. The outputs of these networks ideally exhibit low amplitude and phase mismatches, but their performance heavily depends on precise component selection. The Variable Gain Amplifier (VGA) circuit is a high-frequency RF amplifier comprising MOSFETs, inductors, capacitors, and resistors, each designed to optimize signal amplification and ensure impedance matching. The RF input stage receives the signal source, Vsig, through an amplifier, with Rs acting as the source resistance. The input RF signal (RF_in) is applied to a MOSFET (M1), which enhances the RF signal. By biasing the gate of M1 with VG1 at 0.45V, the MOSFET operates within its amplifying range. Inductors L1, Lg1, and L2 form a matching network to maximize signal transfer efficiency, while a parallel capacitor (C1) and inductor (L2) establish a resonant circuit for frequency-specific amplification, yielding a clear and robust signal at Vo1. The biasing and matching network maintain the stability and functionality of the MOSFET circuit. Biasing resistors (RB, RG1) ensure the MOSFET functions within its designed amplification range. Coupling capacitors, such as an 8.27 pF C2, block DC components in the signal path, preventing DC offsets from affecting subsequent stages and preserving signal integrity. The circuit's second amplification stage, comprising MOSFETs M2, M3, and M4, further amplifies the signal. A cascaded structure involving M2 and M3 enhances gain and isolates input and output stages. Drain currents (ID2, ID3, ID4) reflect the operating conditions of these MOSFETs, demonstrating their ability to handle current demands during amplification. This stage enables high amplification with minimal output load interference, delivering the final RF signal to the load (RL) with reduced losses. Voltage biasing plays a crucial role in ensuring proper MOSFET operation during amplification. Gate voltages (VG1, VG2) define the operating points of M1 and M2, while drain bias voltages (VD1, VD2) provide the necessary power to drive the MOSFETs and maintain signal amplitude across stages. Inductors L6, L7, and L4 fine-tune the circuit at target frequencies, enhancing amplification efficiency during high-frequency RF operations. A feedback resistor (Rb3) stabilizes the amplifier, preventing oscillations and ensuring consistent gain under variable signal conditions. Additionally, a variable control voltage (Vctrl), typically ranging from 0 to 1.2V, allows for dynamic adjustment of M4’s performance. This feature is essential for RF applications, where environmental changes or varying operating conditions necessitate flexible gain control to maintain signal quality and adapt to the environment.

3. Results

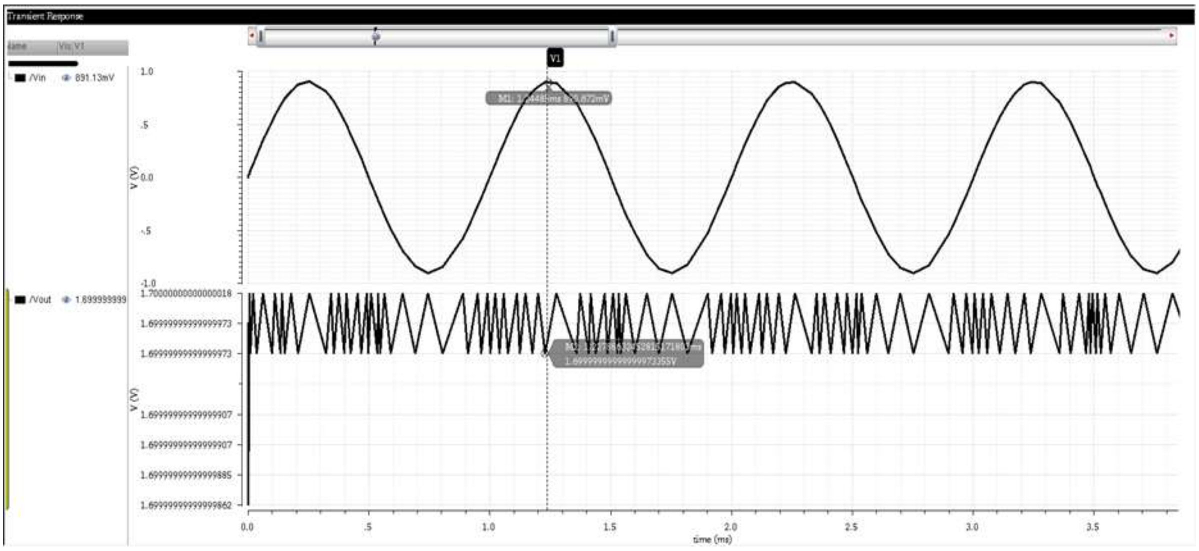

Fig.3.1 output-1 with the input of 900mV and it amplified to 1.7mV.

The paper describes the successful design of two key components for RF and microwave systems. First, it is a CMOS Variable Gain Amplifier operating in the frequency range 22.7–29.7 GHz. The VGA achieves a wide gain tuning range from 19.2 dB to -4.5 dB with a total span of 23.7 dB, with an average noise figure of 3.26 dB and a power consumption of 7.4 mW. These features make it very efficient and suitable for high-frequency communication and radar systems, ensuring precise gain control and optimal signal quality under a variety of operating conditions. It involves the Ku-Band 6-Bit Vector Sum Phase Shifter for working within the frequency band between 12 and 18 GHz. This particular shifter achieves 64 steps on discrete phase with half quadrants for fine adjustment phases. It is applied specifically where precise control results directly into performance in the phase array antennas and systems because the half-quadrant also improves phase coherence hence utmost directionality and stability with its signals. Overall, the paper demonstrates how these advanced VGA and phase shifter designs improve adaptability and performance in RF and microwave systems. The findings emphasize the critical role of precise gain and phase control in developing efficient, high-frequency signal processing solutions for modern communication and radar applications.

4. Conclusion

This paper discusses two major components for RF and microwave systems: a low-power CMOS Variable Gain Amplifier (VGA) and a Ku-Band 6-Bit Phase Shifter, both of which provide significant improvements in performance and functionality. The VGA is designed to operate at 22.7–29.7 GHz with a 23.7 dB gain tuning range and an average noise figure of 3.26 dB. These features make it suitable for high-frequency communication and radar systems, where efficient power usage, precise gain control, and robust performance under varying conditions are critical. The design ensures reliable signal quality, meeting the stringent demands of modern RF applications. The Ku-Band Phase Shifter complements this by offering 64 discrete phase steps across the 12–18 GHz range, incorporating half-quadrant control for improved phase coherence and fine-tuned adjustments. This capability is especially valuable for phased-array antennas and radar systems, where precise beam steering and phase alignment have a major impact on efficiency and overall system performance. The design of the phase shifter ensures that there is more signal directionality and stability, addressing critical needs of applications such as satellite communication, wireless backhaul, and advanced radar technologies. Together, these designs represent a significant step forward in adaptability and performance for high-frequency signal processing solutions. They point to the need for precise gain and phase control to overcome the challenges of changing RF and microwave systems. With low power consumption, high accuracy, and innovative control features, these components will be the basis for the development of more efficient, scalable, and versatile technologies in modern communication and radar systems

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