A 10-bit Active RF Phase Shifter for 5G Wireless Systems

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Abstract—This paper presents an active RF phase shifter with 10 bit control word targeted toward the upcoming 5G wireless systems. The circuit is designed and fabricated using 45 nm CMOS SOI technology. An IQ vector modulator (IQVM) topology is used which provides both amplitude and phase control. The design is programmable with exhaustive digital controls available for parameters like bias voltage, resonance frequency, and gain. The frequency of operation is tunable from 12.5 GHz to 15.7 GHz. The mean angular separation between phase points is 1.5 degree at optimum amplitude levels. The rms phase error over the operating band is as low as 0.8 degree. Active area occupied is 0.18 square millimeter. The total DC power consumed from 1 V supply is 75 mW.

Keywords—CMOS, SOI, beamforming, RF, phase shifting, phased arrays, wireless communications, 5G, IQVM.

I. INTRODUCTION

The expectations of achievable data rates in 5G are approximately a 1000 fold higher compared to current 4G data traffic standard. To achieve these higher data rates, wide band systems operating at centimeter or millimeter wave (mmWave) frequencies are required [1]. Substantial path loss along with the difficulty of RF power generation at these frequencies necessitates using phased array systems with beam steering capabilities [2]. In addition to very high data rates for individual connections, fifth generation wireless systems also target extremely high traffic density. Therefore, sidelobe level reduction to minimize out-of-beam interference is essential. To achieve that, 10 dB of RF amplitude control range will be typically required.

In this paper, we describe an active RF phase shifter targeted towards 5G communication systems. The phase shift is achieved using an IQ vector modulator (IQVM) topology. The design is capable of operating from 12.5 GHz to 15.7 GHz, which is appropriate for prototyping although recent interests in 5G are at 28 GHz, or above. The 10 bit control word encodes both phase and amplitude information and provides 10 dB of RF amplitude control, which is required for amplitude tapering applications.

The organization of the paper is as follows, in Section II, architecture and circuit design for all the related blocks is described, followed by the measurement results in Section III. Conclusions are drawn in Section IV.
A. Polyphase Filter

Polyphase filter can be understood as a combination of low pass and high pass filter [3]. The manner in which the input signal is fed to the polyphase filter, it can be classified into two types; Type-I which has a constant phase difference and Type-II which has a constant amplitude [5]. Here, a constant phase topology is used. Instead of using the traditional interdigitated metal finger capacitors, MOS transistors are used as a capacitive element due to the fact that they are easy to control via digital logic. Furthermore, small capacitance values can be realized more accurately with lower parasitic capacitance.

The complete structure of the implemented polyphase filter is shown in Fig. 3. Transistor M1 and M2 are used in a common source topology and are providing DC bias to M3–M6. The DC bias for M1 and M2 is provided by using a variable current source along with a diode connected transistor M2. As the bias point of the common source stage can be digitally controlled, this inherently gives a control over the realized capacitance value, thus, by changing the bias, the corner frequency of the polyphase filter can be digitally controlled. To keep the gain loss to a manageable level, a single stage polyphase filter was implemented at the cost of its bandwidth.

B. IQ vector modulator

At block level, the IQVM consists of two sub blocks, the first one is for dictating the sign of the basis vector and the second block is a voltage controlled current source (VCCS), which performs the vector addition, as shown in Fig. 4. In order to change the sign of a vector, cross connected MOS switches are used. Thus, in total, two bits out of ten are used for selecting the appropriate quadrant. As resistive load is used in the summing node, dimensioning for four bits of binary weighted pseudo differential tree becomes difficult because of the limited available voltage swing. To circumvent it, the least significant bit for both I and Q branch is implemented with a unit element, which bleeds only half of the current from the load resistor, with the other half coming directly from the supply. Thus, rather than using 1X, 2X, 4X and 8X size elements, 1X, 1X, 2X and 4X size elements are used in the binary weighted tree. The schematic of the positive side of the binary weighted tree is shown in Fig. 5.

C. Driver

The schematic of the driver stage without the biasing structures is shown in Fig. 6. Transistors M8 and M9 along with the variable current source form a differential amplifier. A variable LC tank comprising of a fixed inductor L1 and a bank of binary weighted capacitors, denoted here by C1, is used as a load. The differential output is converted to single ended using a pseudo-differential amplifier consisting of M4 to M7. Transistor M3 is in a common source topology with a variable resistive load, implemented by connecting digitally controlled MOS in parallel to a fixed resistor. The main purpose of it is to provide a coarse gain control. Finally, the output is taken from a cascode stage consisting of M1 and M2.

The width of the transistors in the driver is gradually increasing, with M8 being 18 µm and M1 being 523 µm. In order to effectively drive such a large device, an input resonator consisting of a fixed inductor L2 and a variable capacitor C2 is used. By changing the value of C2, frequency response of the stage can be altered. Furthermore, it allows the output DC feed inductor L1 and coupling capacitor C1 to be chosen more freely, which are jointly optimized to maximize the Q value in order to maximize the gain. Since, the resistive parasitics of L2 has a significant impact on the Q factor of the resonator, by taking the signal out from the center tap of the L2, the sensitivity to the resistive parasitics is reduced to a large extent.

III. Experimental Results

The developed active phase shifter integrated circuit (IC) is fabricated using 45 nm CMOS SOI technology and its
The micrograph is shown in Fig. 7. The dimensions of the IQVM including the input and output pads is 1.0 mm × 0.4 mm. The core area of the IQVM is 0.18 mm$^2$ and is circled by a black rectangle in Fig. 7. The maximum DC power consumed from 1 V supply by the IQVM is 75 mW. The IC is flipped and bonded directly onto the printed circuit board (PCB) via solder bumps. The four layer PCB was manufactured using Isola Astra MT77.

Vector signal measurements are done using Keysight PNA-X N5247A. Due to the absence of an external absolute phase reference, a fixed digital control word of the IQVM is considered as a reference for all phase measurements. Hence, no calibration is applied to the phase measurements. Since only relative phase and magnitude information is of interest, the lack of calibration is not a hindrance in interpreting the results. All 1024 different phase and amplitude points is shown in Fig. 8. It can be seen from the figure that there is a marginal skew in the measured phase constellation, which implies that the phase difference between the I and Q basis vectors is not 90° but rather close to 85°. Furthermore, it seems that in the fourth quadrant ($A_I \geq 0, A_Q \leq 0$, lower right half) the gain is marginally smaller compared to other three quadrants.

It is inherent in the design of an IQVM that there are more number of phase points at higher gain settings compared to lower gain settings i.e., the phase resolution is not independent of the gain. This leads to a case where multiple phase points have similar magnitude and the phase difference between them is less than 0.5° i.e., for all practical purpose they are indistinguishable. To quantify this reduction in control space, the number of effective bits is defined as $\log_2 N_u$, where $N_u$ is the total number of unique phase points over the available magnitude range. Here, unique phase points are defined as phase points which have a phase difference of at least 0.5° given the difference in their magnitude is less than 1 dB. The available number of unique phase points as a function of their normalized magnitude is plotted in Fig. 9. It also depicts the mean angular separation as a function of normalized gain. It can be seen from Fig. 9 that the behavior of the IQVM is similar over the operating frequency band. Compared to an idle IQVM, i.e., one which does not suffer from issues like component mismatch, gain mismatch, or compression, the realized IQVM suffers marginally in terms of unique phase points. The rms phase error for a fixed digital configuration of the resonance controls is shown in Fig. 10. It can be seen that the minimum rms error occurs at 15.0 GHz.

The normalized frequency response of the IC for different digital configuration of the resonance controls is shown in Fig. 11. The blue and the black curves illustrate the tuning range of the resonance controls. It can be seen from the figure that the 3 dB tuning range is from 12.5 GHz to 15.7 GHz.
Furthermore, the 3 dB bandwidth for a given digital configuration is 2.5 GHz. Finally, a summary of the key performance parameters is shown in Table I.

IV. CONCLUSION

In this work we demonstrated a package-less active phase shifter IC targeted toward 5G communication systems. The measured mean angular separation between phase points was 1.5° at optimum amplitude levels. The minimum rms phase error was 0.8° and occurred at 15.0 GHz. The designed phase shifter could operate over a frequency range of 12.5 GHz–15.7 GHz with a RF bandwidth of 2.5 GHz. The DC power consumed was 75 mW.

ACKNOWLEDGMENT

The research leading to these results has received funding from the Nokia Corporation Ltd. The authors would also like to acknowledge Global Foundries for the silicon processing and technical support. Support provided by Ganesh Venkatraman, Nuutti Tervo, Risto Vuohioniemi and Saila Tammelin is highly appreciated.

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