A 60 GHZ ANALOG PHASE SHIFTER IN 65 NM BULK CMOS PROCESS

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ABSTRACT

A 60 GHz Analog Phase Shifter in 65nm bulk CMOS process has been explored for microwave frequency applications. It is an analog phase shifter with three transistors in the form of an active circulator and a LC network to attain the desired phase shift. This phase shifter is designed to work at a high frequency of 60 GHz to attain phase shift range of 140°. The proposed phase shifter works at supply voltage lower than 2.5 V. The phase shifter exhibits low insertion loss of 3.73 dB and low power consumption which is a challenging result for circuits working in microwave frequencies.

KEYWORDS

60 GHz phase shifter, 65 nm CMOS, Active circulator

1. INTRODUCTION

Phase shifters are the devices used to adjust the transmission phase in a system. The main operation behind a phase shifter is it allows adjustment of insertion phase. They are widely used in the field of RF communication in phased arrays and in frequency translators. The performance of such systems greatly depend on the phase shifting component. Depending on the application one may require either an analog or digital phase shifter. The digital phase shifter provides a constant phase over a specific bandwidth and the analog phase shifter provides continuously controlled phase shift over a wide range of frequencies [1]. Various topologies have been proposed for the development of phase shifters [2]-[3]. The first topology is the distributed type phase shifter with loaded transmission lines is widely used due to its low insertion loss [4]. This technique requires transmission lines with lengths proportional to the signal wavelength. The major drawback in this approach is the large chip size. If we replace the transmission lines with active LC components the chip size can be reduced [5]. The second topology is the Forward Type phase shifter (FTPS) [6]-[7] which depend on couplers (transmission line) to split the input signal into multiple signals for processing and combine them at the output. This phase shifter requires many couplers for combining the multiple signals at the output, resulting in large chip area due to the presence of many passive couplers. The Third topology is the Reflective Type Phase Shifter (RTPS) [8]-[10] which is more compact since it uses the same coupler (transmission line) to split the signals and combine them at the output. The couplers can be replaced by active components in order to reduce the chip size. Phase shifters using spiral inductors exhibit high insertion loss and limited phase shift [11]. The passive couplers in the FTPS and RTPS can be replaced by active LC components to reduce the size of the phase shifter. The other topologies are loaded line phase shifter (LL) [12], switched line phase shifter (SL) [13] which exhibits large insertion loss and the high pass or low pass (HP/LP) phase shifter [14]. All these phase shifters have passive components in the form of couplers (transmission lines) which results in large chip size. While considering phase shifters

working in 60 GHz, a digitally controlled phase shifter is developed [15] which involves the usage of transmission lines and exhibits insertion loss of 8.5 to 10.3 dB, return loss above 10 dB and phase range of 180^{o}. A digitally controlled phase shifter in 60 GHz is developed in 65 nm CMOS with noise figure as 7.2 dB , phase shift range of 360^{o} and chip area of $1.6mm^2$ [16]. A phase shifter both passive and active in 60 GHz is designed with a phase shift range of 180^{o} in passive phase shifter, insertion loss of 4.2 dB to 7.5 dB, noise figure of 16.5 dB and phase shift range of 360^{o} in the active phase shifter [17]. Considering the chip size and performance, it is better to use active phase shifter with transmission lines replaced by lumped elements such as the LC network. At microwave frequencies, the continuous phase shift can be obtained by using RTPS with a varactor. For frequencies above 10 GHz it is not feasible to use analog phase shifters with varactors because the capacitance required for the phase shift is smaller (less than 0.1 pF), and the parasitic reactance degrades the performance of the phase shifter. Therefore, it is very difficult to find voltage controlled analog phase shifter for frequencies above 10 GHz [18].

In this paper, an analog phase shifter working at the frequency of 60 GHz is proposed and demonstrated experimentally in 65 nm bulk CMOS process for microwave frequency applications. Here we use an active circulator and a series LC network to make the circuit fully active and compact. This phase shifter is designed in such a way to attain a phase shift range of 140^{o}**.** This proposed phase shifter exhibits low insertion loss over a high frequency band and low power consumption. The main advantage in using 65 nm bulk CMOS process is low cost, low insertion loss and high performance.

2. PROPOSED ANALOG PHASE SHIFTER

A circulator was proposed and demonstrated using bipolar transistors in the range of megahertz [19] in the year 1965. Later modifications were made and was designed for microwave frequencies with GaAs FETs with supply voltages above 10 V [20]. In later years the circulator was redesigned in 180 nm CMOS process for a supply voltage of 3.5 V and frequency of 2.4 GHz [21]. We have redesigned the circulator using 65 nm CMOS process for a frequency of 60 GHz and minimized the supply voltage to 1.2 V.

Figure.1 shows the block diagram of the proposed analog phase shifter. It is a phase shifter based on an active circulator consisting of three ports namely P1, P2 and P3. Active circulator is a three terminal device in which input from one port is transmitted to the next port in rotation. The circulator acts as an isolator between the input and the output signal so that phase shift is well observed. The RF input signal is given at P1 of the circulator from the left side. This signal from P1 is transmitted to P2. The LC components are in series with P2 which results in the desired phase shift and helps to reflect the signal to P3 at the right. At P3, we get the desired RF output. Desired phase shift can be attained by either tuning L or C connected to P2. Initially during simulation we have assumed that the active circulator and the LC elements are lossless. In order to find out the value of L and C, we have considered the following expression.

$Z = j\left(\omega L - \frac{1}{\omega C}\right)$ where $\omega = 2\pi f$. The resonant frequency is obtained by $f = \frac{1}{2\pi\sqrt{LC}}$

Figure. 2 shows the schematic diagram of the active circulator. The active circulator used in this circuit is a three port circulator. It has three nMOS transistors interconnected with each other. R_F , R_D , R_S and C_F play a major role in the working of the circuit. The three feedback resistors (R_F) provides negative feedback in each transistor. The three feedback capacitors (C_F) are used to link all the three transistors in an end to end fashion. The source resistor (R_S) is shared among all the three transistors and one transistor is source coupled with the other two transistors using this source resistor. Three source degenerators are used in the circulator. The circuit works in a

symmetric fashion. The supply voltage (V_{DD}) is given for each transistor. Same DC voltage is given in all ports of the circulator to bias the transistors.

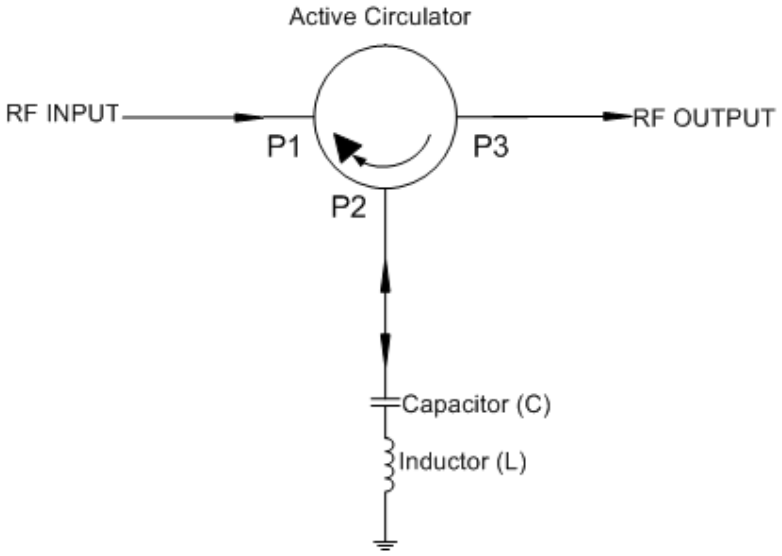

Figure 1. Block diagram of proposed phase shifter

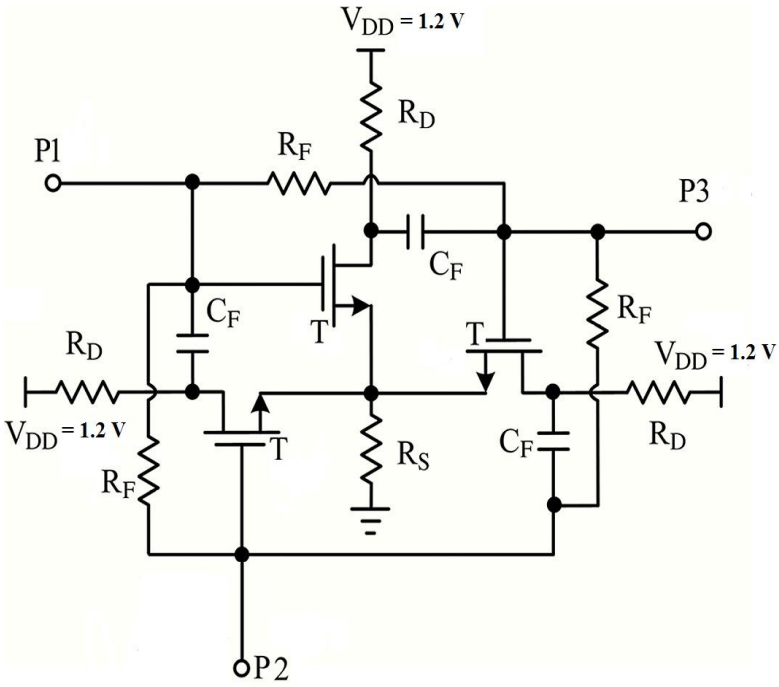

Figure 2. Schematic diagram of the active circulator

3. SIMULATION RESULTS

Figure.3 shows the insertion loss of the circulator. Considering the frequency range of 57 GHz to 65 GHz, the insertion loss is simulated and experimentally proved to be low. The insertion loss for this phase shifter is 3.7 dB for the frequency range of 60 GHz. Figure.4 shows the reflection parameters of the circulator. By further calculation, return loss is obtained as 20 dB. Since the circuit is working in a symmetric manner the input and output return loss are the same for the frequency range of 57 GHz to 65 GHz. The LC network has an inductance of approximately L = 74 pH and capacitance of approximately C = 95 fF. This results in a resonant frequency of 60 GHz. During simulation to attain phase shift the circuit is tuned for the transmission coefficients to get close to 0 dB and by varying the capacitance and inductance in the LC network the desired phase shift is attained. To characterize the linearity of this phase shifter the output power versus input power is measured and the input P1(dB) is 5.129 dB. The maximum power consumption for the circuit is 20 mW with a supply voltage of 1.2 V.

When compared with many topologies this proposed phase shifter consumes less power to give high performance due to scaling in technology size to 65 nm bulk CMOS Process. Figure.5 shows the noise figure for the desired frequency range which is 18.56 dB for 60 GHz. Phase shifters using active components have high noise figure than the phase shifters using passive components. Since the passive components include couplers using transmission lines they don't have much noise. While using active components like transistors, capacitors and resistors, the noise figure is higher. If the phase shifter is used in a receiver then the noise figure should be less. If this phase shifter is used in a transmitter then high noise figure is negligible.

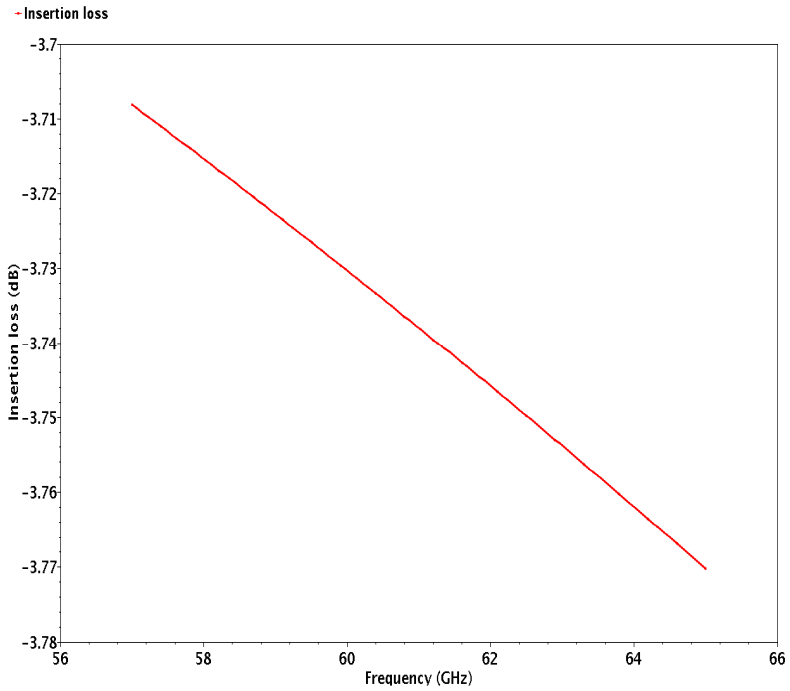

Figure 3. Insertion loss

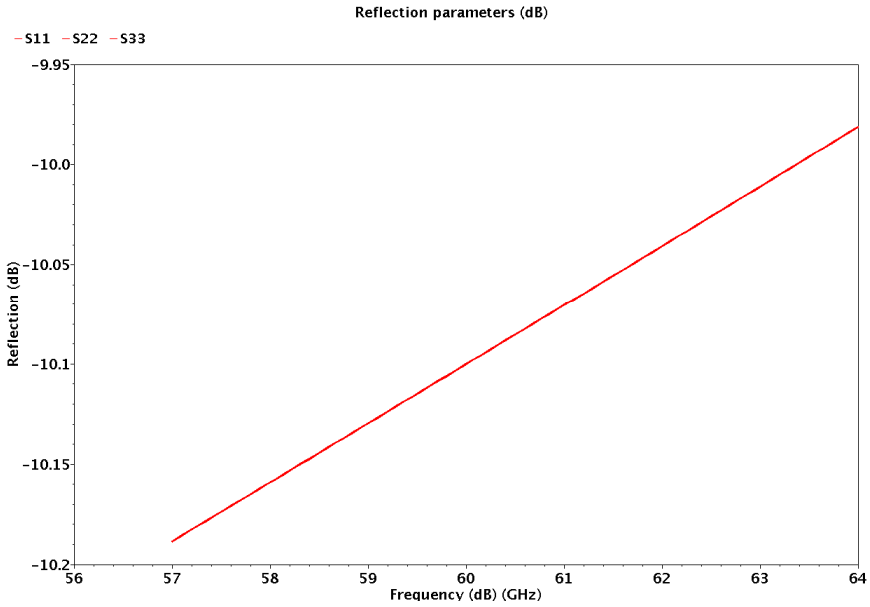

Figure 4. Return loss

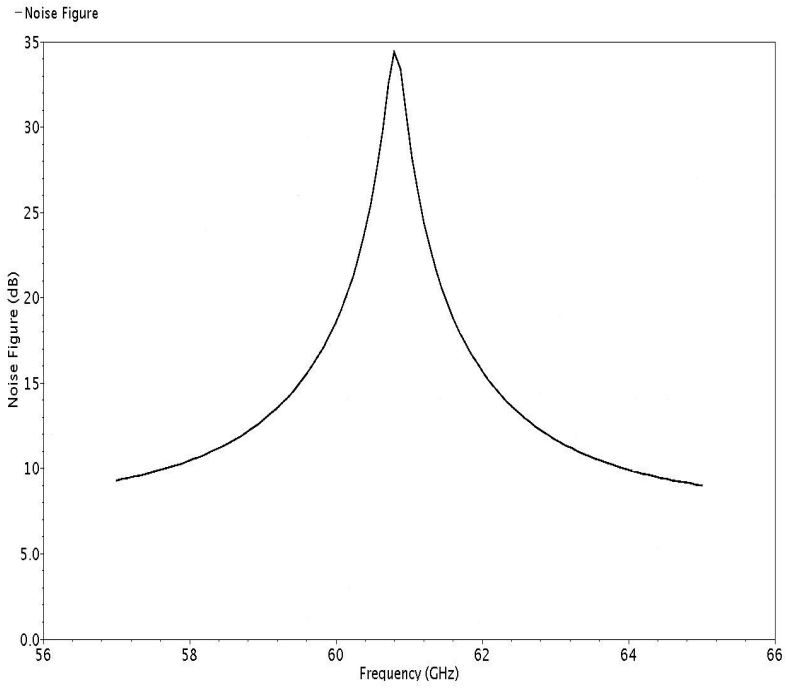

Figure 5. Noise Figure

Table 1. Performance summary of the phase shifter

Technology	65 nm bulk CMOS
Frequency (GHz)	60
Max.insertion loss (dB)	3.73
Power consumption (mW)	20
Noise figure (dB)	18.56
Input P1dB (dBm)	5.129
Return loss (dB)	20
Phase shift range	140^{o}

3. CONCLUSION

This paper has presented the development of a 60 GHz phase shifter in 65 nm bulk CMOS technology. The phase shifter consists of an active circulator and a LC network. The circulator is very small with only three transistors which are connected end to end in a ring which makes the design more compact. This phase shifter exhibits low power consumption and low insertion loss. Return loss is 20 dB. Since the technology is more advanced than the most popular 180 nm technology, the performance is high enough for a phase shifter working at 60 GHz. This phase shifter exhibits a phase shift range of 140^{o}.

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