Millimeter Wave Front-End CMOS ICs for Phased-Array Transceivers

Alex Chung, Student Member, IEEE and Bhaskar Banerjee, Member, IEEE

***Abstract*—Significant increase in CMOS operating frequencies due to aggressive scaling has allowed us to design CMOS circuits up to high millimeter wave (mmW) range with decent performance. However, several challenges still remain including low output power from CMOS transmitters at mmW frequencies and high loss in the CMOS substrate. In this project report, different approaches to phase shifters, both active (current steering band pass phase shifters) and passive (delay line), will be investigated in standard CMOS process.**

Keywords—Active phase shifter; Passive phase shifter

I. Introduction

Phase shifters are responsible for changing phase in a system. In order to control beam-steering systems, many different phase shifter designs are introduced. Mainly, there are two types of phase shifters: active phase shifters and passive phase shifters.

II. Active phase shifter

Active phase shifter is a phase shifter which uses active components. An active component is a component that is capable of providing a power gain. They inject power to the circuit and control the current flow within the circuit. Transistor is one example of active components. In this section, examples of active phase shifter designs will be introduced.

1) *Analog Differential Adder*

Figure 1 shows the analog differential adder. I/Q input polarity can be reversed by switching on and off the S_I and S_Q.

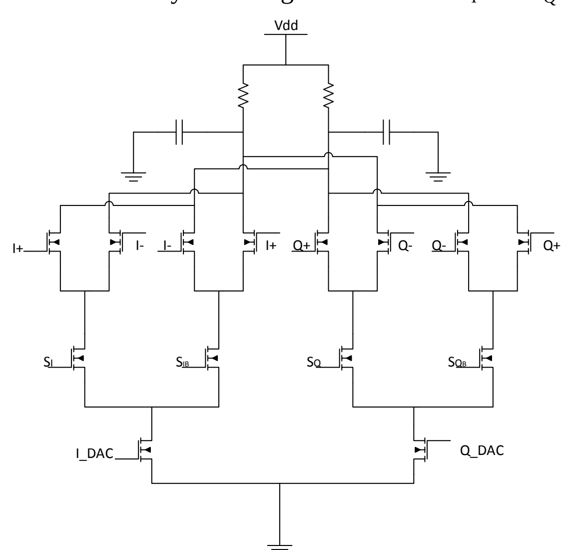

Figure 1. Analog Differential Adder

2) *Current Digital-to-Analog Converter*

In order to design 22.5° phase shifter, varying transconductances of input transistors by using a current DAC and adding its small signal drain currents with a differential adder is necessary. Since gain is proportional to square root of current, by varying current flow through the transistor, phase shift can be determined by, θ= tan-1($\sqrt{I_I}/\sqrt{I_Q}$).

Figure 2 shows three-bit differential DAC for bias current controls of the adder. Since phase shift is determined by the ratio of the bias current, $\theta = \tan^{-1}(\sqrt{I_I}/\sqrt{I_Q})$, the size of the MOSFETs should be determined accordingly. In order to give 22.5° shift, ratio of I_I and I_Q 1 to $\sqrt{6}$ gives a good approximation.

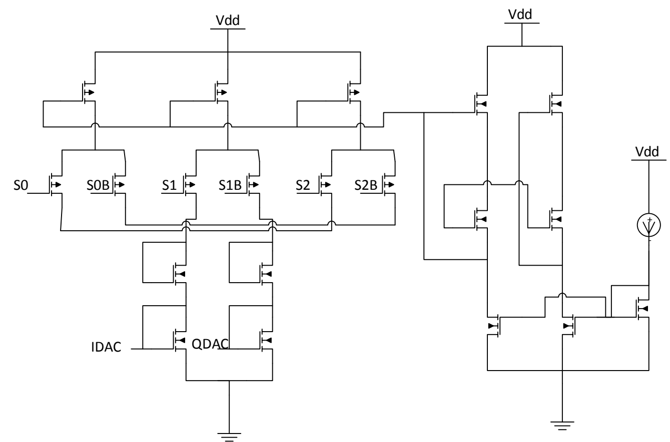

Figure 2. Three-bit current DAC

3) *Results*

All possible phase rotations are shown in Figure 3.

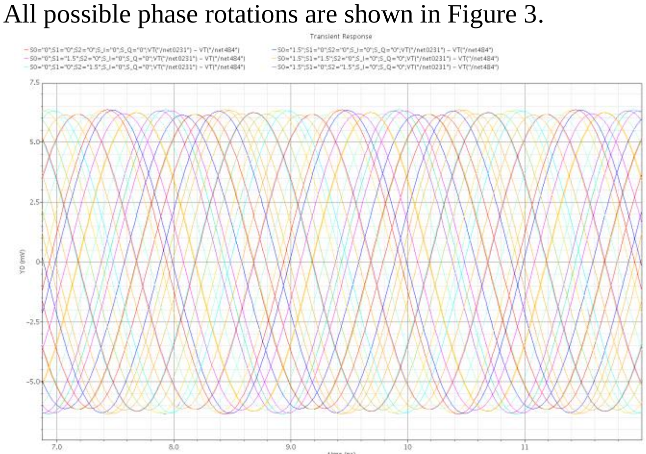

Figure 3. Results of Phase Shifts

The authors are with the Texas Analog Center of Excellence (TxACE) at the University of Texas at Dallas (UTD), Richardson, TX 75080 USA

The sum of two bias currents remains the same for all phase bits. As a result, with constant load impedance, amplitude remains the same.

III. PASSIVE PHASE SHIFTER

Passive phase shifter is a phase shifter which uses passive components. A passive component is a component that is not capable of providing a power gain. They cannot control the current flow in the circuit. Resistors, capacitors, inductors are examples of passive components.

1) *Loaded-Line Phase Shifter*

One of the disadvantages of single loaded-line phase shifter is that as phase shift increases, insertion loss also increases. However, additional shunt susceptances separated by 90 degree will greatly improve this disadvantage. 90 degree transmission line is chosen because insertion loss is minimized between two components separated by λ/4 (90 degree). For ADS simulation, the switched line attenuator using a 90 degree micro-strip line for 4GHz is done. For the capacitive value of 0.2 and inductive value of -0.2, phases are 78.7° and 101.3°, respectively. Therefore, phase difference between two is around 22.5 degree. To obtain other phase shifts, let x and y are two different phases that are added up to be 180°. The difference of x and y has to be a phase differece that needs to be obtained. For example, to design 45° phase shift, the difference between x and y has to be 45°. Therefore by using following equations:

$$x+y= 180 \qquad x-y = 45$$

As a result, x is 112.5° whereas y is 67.5°. Since equivalent phase length is $\cos^{-1}(-b)$, b is equal to cos(112.5°) and cos(67.5°) which is -0.382 and 0.382, respectively. When N is 50Ω and b=0.382, inductive and capacitive values at 4GHz frequency are:

- $L=\frac{N}{wB} = \frac{50}{2pi(4GHz)(0.382)} = 5.2\text{nH}$
- $C=\frac{B}{wN} = \frac{0.382}{2pi(4GHz)(50)} = 0.305\text{pF}$

The table below shows all the possible phase shifts and inductive and capacitive values according to those phase shifts.

Phase Shift (°)	L(nH)	C (pF)
22.5	9.9	0.159
45	5.2	0.305
67.5	3.58	0.442
90	2.81	0.563
112.5	2.39	0.617
135	2.15	0.735
157.5	2.03	0.781

Table 6.

IV. CONCLUSION

In this report, different approaches to phase shifters, both active (current steering band pass phase shifters) and passive (delay line) are introduced and compared. In conclusion, the advantages and disadvantages of active and passive phase shifters are discussed.

A. *Active phase shifters*

1) *Advantages*

a) Gain can be attained.

2) *Disadvantages*

a) The circuit design is complex to achieve small phase shifts (less than 11.25°) becuause active phase shifters vary the phases by controlling currents through each transistors and obtaining approrpirate ratios of currents through each transistors is difficult.

b) Accurate phase shifts are difficult to be obtained because there is limitation on DC current change.

c) Linearility should be maintained

d) Large power consumption is usually requred to achieve a high dynamic range.

B. *Passive phase shifters*

1) *Advantages* It is possible to achieve accurate phase shifts using delay lines by varying the propagation constant of transmission line (by changing a capacitance value).

a) It can provide continuous phase shifts.

b) It is the most power efficient architecture.

2) *Disadvantages*

a) Many number of switches are needed to achieve accurate phase shifts.

b) It tends to be lossy in the transmission lines

c) Delay elements are area consuming

V. NEXT CAREER PLAN

The MTT-S scholarship program gave me an opportunity to research on RF related topic as an undergraduate student. The MTT-S scholarship also motivated me to further pursue my Master's degree and encourage me to further my graduate education in the related field.

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