A Miniature Low-Insertion-Loss, High-Power CMOS SPDT Switch Using Floating-Body Technique for 2.4- and 5.8-GHz Applications

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Abstract — A low insertion loss SPDT switch in standard 0.18- μm CMOS process was developed for 2.4- and 5.8-GHz WLAN applications. In order to reduce the insertion loss and increase the P_{1dB} , the floating-body circuit topology is proposed. The series-shunt switch achieves a measured P_{1dB} of 20 dBm, an insertion loss of 1.1 dB, and an isolation of 27 dB at 5.8 GHz. It also achieves a measured insertion loss of 0.65 dB and an isolation of 35 dB at 2.4 GHz. The effective chip size is only 0.03 mm². The measured data agree with the simulation results well. To our knowledge, this work presents the low insertion loss, high isolation and good power performance with the smallest chip size among the previously reported 2.4- and 5.8-GHz CMOS switches.

Index Terms — CMOS, SPDT switch, body floating.

I. INTRODUCTION

In recent years, wireless communication systems have undergone explosive growth that is largely unanticipated. Much of this growth has been in complementary metal-oxide semiconductor (CMOS) technology. CMOS technology has been able to meet the more stringent cost constraints inherent in these more diverse mainstream applications. The advantages of silicon CMOS technology for RF and microwave control functions over GaAs are its low cost structure and its integration potential with RF and silicon MOS-based mixed-signal circuitry. A high-quality microwave switch is a key building block of a RF front end for time-division duplexing (TDD) communication systems. To further increase the integration level, the SPDT switch has to be integrated in the transceiver.

Switches using high performance processes such as GaAs HEMTs were designed for digital mobile communication systems [1]. However, due to the advantages of low cost and integration capability with baseband circuits, the CMOS RF chips are getting more attractive. Key figures of merit of a T/R switch are insertion loss and power handling capability measured by the power 1-dB compression point (P_{1dB}) [2]-[5]. Switches using high and low substrate resistances in a 0.18- μm CMOS process have demonstrated good insertion loss [6], but it requires a large area of substrate contact to implement a low substrate resistance switch. To achieve such performance, a LC-tuned substrate bias was used [7]. However, the bias network improving the large-signal handling capability increased the chip size greatly. In the meanwhile, the LC-

tuned substrate bias network limits the switch in a narrow frequency range. For 2.4-GHz and 5.2-GHz applications, two different switches are designed and the LC-tuned substrate bias networks are needed to be devised respectively. Impedance matching technique was used to improve the P_{1dB} of the switch [8], but the matching network resulted in a large die size, also. Switch realized by depletion-layer-extended transistors (DETs) obtained high power-handling [9]. Nevertheless, the DETs are formed with the addition of more mask steps than the standard CMOS process, and in order to avoid latching up, the pMOS and n-well must be placed sufficiently far away from the DETs, and thus results in a large chip size.

In this paper, CMOS RF SPDT switches in standard 0.18- μm CMOS process are presented. Using the body-floating technique, this approach demonstrates high power-handling with a miniature chip size. The SPDT switch exhibits 0.65-dB insertion loss, 35-dB isolation at 2.4 GHz and 1.1-dB insertion loss, 27-dB isolation, 20-dBm output P_{1dB} at 5.8 GHz. Table presents the recently reported performances of 5-6 GHz CMOS switches. Compared with the CMOS switches at 5.8 GHz, the chip accomplished the low insertion loss, high isolation, good power performance and smallest chip size simultaneously.

II. BODY FLOATING TECHNIQUE

The SPDT switch is fabricated in a 0.18- μm CMOS process, which provides single poly layer for the gates of the MOS and six metal layers for inter-connection. As shown in Fig. 1, deep n-well (DNW) is offered as default in 0.18- μm mixed-signal process for better substrate isolation with an additional PN junction [10]. In this work, DNW is used to absolutely separate the body of the transistor with the p-substrate in the body-floating technique. Because of DNW, the switch can get rid of latching up.

The insertion loss of the switch was analyzed using the nMOS small signal model. As shown in Fig. 2, R_s represents the substrate resistance associated with the transistor. C_T stands for the equivalent capacitance and can be represented as:

TABLE I
RECENTLY REPORTED PERFORMANCE OF 5-6GHz CMOS SWITCHES.

Process	Frequency (GHz)	Insertion loss (dB)	Isolation (dB)	P_{1dB} (dBm)	Effective Chip Size (mm ²)	Design Features	Ref.
0.18-μm CMOS	5.8	0.8	30	17	0.21*	Low substrate resistance	[6]
0.18-μm CMOS	5.2	1.5(Tx)	30(Tx)	28(Tx)	0.56	LC-tuned substrate bias	[7]
		1.4(Rx)	15(Rx)	12(Rx)			
0.18-μm CMOS	5.0	0.95(Tx)	26.3(Tx)	22.7(Tx)	<0.1	Stacked transistor configuration with DETs	[9]
		1.44(Rx)	22.2(Rx)	18.4(Rx)			
0.18-μm CMOS	5.8	1.1	27	20	0.03	Body-floating	This Work

* Total chip size including pads.

$$C_T = C_{DB} + C_{SB} + \frac{(C_{GD} + C_{GS})C_{GB}}{C_{GD} + C_{GS} + C_{GB}} \quad (1)$$

From [2], the insertion loss and the isolation of the switch are determined by C_T and R_B . The insertion loss is maximized when

$$R_{B(max)} = \frac{1}{\omega C_T} \quad (2)$$

Usually, the value of R_B is close to $R_{B(max)}$ for transistors in the typical silicon processes which is not desired. To improve the insertion loss, the R_B should be either extremely large or close to zero. In fact, it is impossible to make R_B zero due to the parasitic effect, and thus how to let R_B be large enough is important. Furthermore, the parasitic capacitance associated with the body will seriously affect the impedance of the switch when the body of the transistor is connected to ground (RF short). Therefore, the body is connected to ground with 5-kΩ resistor as shown in Fig. 1. The resistor provides an open circuit for the RF signal to improve the insertion loss without affecting the impedance of the switch.

Fig. 1. A simple structure of DNW.

Fig. 2. Small signal model for a NMOS operating in the passive model.

Fig. 3. Large-signal model of the device.

The body-floating technique also increases the power handling capability of the switch. Figure 3 shows the large-signal model of the device. In the on state, when the input power is high enough, the parasitic diodes between

drain/source and body will turn on. The waveform of the input signal is then clamped, and the P_{ldb} of the circuit will be limited. When the body of the device is floating, the parasitic diodes will not turn on even if the input power is high enough, and thus the P_{ldb} is improved. The simulated voltage waveforms of the output port of a 180- μm series transistor are shown in Fig. 4, with the input power of 22 dBm. The difference between the peak values of the two different voltage waveforms is about 1.1V.

Fig. 4. Simulated voltage waveforms of the output port in on-state transistor.

III. CIRCUIT DESIGN

By using body-floating technique, the insertion loss, isolation and power handling of the CMOS switch can be improved. Figure 5 is the schematic of the series-shunt CMOS RF SPDT switch which comprises two series and two shunt transistors. The series transistors M1 and M2 perform the main switching function, and the shunt transistors, M3 and M4, increase the isolation of the switch. It is observed that the ratio of the size for the series transistor to the shunt one significantly influence the performance of the switch, especially for the insertion loss. Figure 6 presents the simulated relation between the insertion loss and the gate width of series and shunt transistors. As can be observed, the size ratio of the series and shunt transistors must be selected properly. In order to achieve a low insertion loss, there are two choices: one is to use a large size for the series transistor and a small size for the shunt one, and the other is simply the opposite, that is, to choose a small size for the series device and a large size for the shunt one. The series transistor with larger size has smaller parasitic resistance and thus attains lower insertion loss and better power performance. For the concern of power handling capability, large devices of 180- μm gate width are chosen for series transistors M1 and M2 in this design while the size of shunt transistors M3 and M4 is 60

μm . The gate bias resistors R_{G1} , R_{G2} , R_{G3} and R_{G4} are 5 k to improve the dc bias isolation.

Fig. 5. Series-shunt switch schematic diagram.

Fig. 6. The relationship between insertion loss and the sizes of the transistors. When the size ratio of the series and shunt transistors is chosen properly, the circuit has the lowest insertion loss.

IV. MEASUREMENT RESULTS

The die micrograph of the series-shunt SPDT switch using 0.18- μm CMOS process is shown in Fig. 7. The chip size is $0.53 \times 0.37 \text{ mm}^2$ and the effective circuit area without pads is only $0.2 \times 0.15 \text{ mm}^2$. The circuit was tested via on-wafer probing. As shown in Fig. 8, the series-shunt switch achieves an insertion loss of 0.65 dB and an isolation of 35 dB at 2.4 GHz. It also achieves an insertion loss of 1.1 dB and an isolation of 27 dB at 5.8 GHz. The measurements agree with the simulation results well. When the dc bias of the Tx and Rx nodes is 0 V, V_{C1} and V_{C2} is 1.8 and 0 V respectively, the switch using 0.18- μm device achieves a P_{ldb} of 20 dBm at 5.8 GHz as shown in Fig. 9. Using devices of the same sizes, another SPDT switch without body-floating technique achieves a P_{ldb} of 18 dBm at 5.8 GHz. The P_{ldb} of the switch is improved 2 dB by using the body-floating technique.

Fig. 7. Die photograph of 0.18- μm CMOS switch. The effective circuit area without pads is only 0.03 mm².

Fig. 8. Insertion loss and isolation of the 0.18- μm CMOS switch. It achieves a 1.1-dB insertion loss and 27-dB isolation at 5.8 GHz.

Fig. 9. Insertion loss v.s. P_{in} of the 0.18- μm CMOS switch. Using the body-floating technique, the P_{idB} of the switch is improved 2 dB.

V. CONCLUSION

CMOS technology is a promising technology for RF and microwave control elements based upon the circuit model

presented and on measurements in 0.18- μm devices. A SPDT switch has been designed, fabricated, and tested. Using body floating technique, it accomplishes the low insertion loss, high isolation, good power performance and smallest chip size simultaneously. The switch exhibits 1.1-dB insertion loss, 27-dB isolation, and 20-dBm output P_{idB} at 5.8 GHz. Since the switch was fabricated using standard 0.18- μm CMOS technology, it can be easily integrated with other front-end circuits to implement CMOS transceivers without requiring any additional mask or post-processing steps.

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