A D-band SPST switch using parallel-stripline swap with defected ground structure

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Abstract: In this paper, we propose a D-band switch design using a parallel-stripline swap hybrid coupler with defected ground structure (DGS). Compared to the conventional transmission line (TL) with high insertion loss at high frequency, the equivalent capacitance introduced by the coupler gap leads to series resonance condition which results in lower insertion loss at the higher frequency. The hybrid coupler enables two additional degrees of design freedom since the capacitance and inductance can be tuned by the structural dimension of the coupler. The fabricated switch with core area of 0.0036 mm² shows measured insertion loss of 1.6–3 dB from 110–134 GHz, return loss of higher than 10 dB and isolation level around 16 dB.

Keywords: CMOS, parallel-stripline swap hybrid coupler, defected ground structure (DGS), single-pole-single-throw (SPST) switch, D-band

Classification: Integrated circuits

References

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1 Introduction

Single-pole-single-throw (SPST) switch is a crucial building block of single-pole multiple-throw (SPMT) switches for time-domain-duplexing (TDD)-based front-ends, switched-beam arrays and multiple-input and multiple-output (MIMO) systems [1, 2, 3]. The main challenge in CMOS millimeter-wave (mm-wave) switches design lies in compensation of the parasitic capacitances of the control transistors. This parasitic greatly affects the switch performances, especially the insertion loss (IL), return loss (RL) and isolation (ISO). Based on the inductive elements that are used to compensate the parasitic capacitances, there are some compensation methods demonstrated for mm-wave switches. The most common method is to employ $\lambda/4$ transmission lines [3, 4, 5]. The use of TLs as the compensating element has the benefit of wide-band characteristic due to its inherent broadband properties. However, the compensation method with TLs occupies large silicon area, leading to higher fabrication cost. To achieve more compact silicon area, He *et al.* proposed using a series inductor to replace TLs [7], the method with inductor can save some silicon area but it is hard to provide a wide-band operating frequency range because of high Q inductors. In addition, the inductor causes excessive loss when the operating frequency is higher than 100 GHz due to skin effect [7]. To alleviate these issues, a low-pass filter with defected ground structure is adopted in the SPST switch design in [8]. The technique has some advantages that compensating the parasitic capacitances more effectively and consuming less silicon area; however, the low-pass filter topology has the problem of operating frequency limitation at high frequency because of its natural low-pass characteristics. Thus, a new architecture for mm-wave switches is desired.

In this paper, a parallel-stripline swap hybrid coupler [9] with defected ground structure (DGS) is proposed as an alternative compensation method. The proposed method is demonstrated in a D-band SPST switch design using 65-nm bulk CMOS process. This fabricated switch achieves a minimum IL of 1.6 dB with a core size of only 0.0036 mm^2 . The paper is organized as follows. Section II describes the analysis and design of the proposed SPST switch. The measurement results that verify the design method are discussed in section III. Finally, the paper is concluded in Section IV.

2 Circuit analysis and design

2.1 Parallel-stripline swap hybrid coupler with defected ground structure

Fig. 1 shows the topology of parallel-stripline swap hybrid coupler with defected ground structure, which consists of two transmission lines at both sides and a defected ground plane. A swap core is constructed using two vertical metallic vias, which are employed to bridge the upper metal layer and bottom metal layer. The defected ground plane consists of two large rectangular slots that are connected by a small gap. For a conventional TL, the current return path on the ground plane is the anti-phase of the current path on microstrip line. The surface current distributions of the hybrid coupler are plotted in Fig. 1. The opening in the ground plane disturbs the return current distribution and thus, the current is confined to the edges of two polygon slots. This results in the enhancement of the effective inductance due to the increase in the length of the current return path.

Fig. 1. Illustration of parallel-stripline swap hybrid coupler with a defected ground structure: (a) 3-D view; (b) Top view; (c) Bottom view; (d) Surface current distribution on the upper metal layer; (e) Surface current distribution on defected ground plane.

At the desired frequency range, the input signal can be coupled to the output port through the coupling capacitance that is introduced by the gap between TL-1 and TL-2 of the hybrid coupler. Hence, this coupling capacitance determines the resonance frequency of the hybrid coupler. Since the capacitance can be tuned by changing the gap dimension, we have an additional degree of freedom to control the frequency response of the coupler and further the switch performance. Unlike the conventional transmission line, the coupling capacitance of the hybrid coupler introduces series resonance condition (zeros) at high frequency, hence we can achieve higher operating frequency with lower loss. Fig. 2 shows the comparison of simulated IL between the hybrid coupler with DGS and conventional TL. As

we can see, hybrid coupler with DGS shows more superior insertion loss performance at high frequency than conventional TL. Hence, we use this structure as alternative compensation method to replace the conventional transmission line in SPST switch design.

In addition, defected ground structure enhances the equivalent inductance of the hybrid coupler, which can be used to compensate the parasitic capacitance of control transistors of the switch. Since the inductance can be tuned by changing the size of the defected area, we have the additional parameter to tune the overall response of the switch. Due to its planar structure, simple fabrication process, and compatibility with CMOS technology, it provides more compact inductive components with low cost for fully integrated advanced D-band systems.

Fig. 2. The EM simulated IL of parallel-stripline swap hybrid coupler with DGS and conventional TL at the same physical size.

2.2 Circuit implementation

Table I. Target specifications for the SPST switch

Design Parameter	Value
Operating frequency (GHz)	110–130
Insertion Loss (dB)	<3
Return Loss (dB)	>10
Isolation (dB)	>15
Input P_{1dB} (dBm)	>10
Core Area (mm ²)	<0.01
V_{ctrl} (V)	0/1.2

A switch is required with the performance of low insertion loss, high isolation, large power-handling capability, and operating bandwidth. Containing great spectrum resources from 110 GHz to 170 GHz, D-band is ideally suitable for short-range and extremely high speed wireless systems. The target of designing the SPST switch is to construct the single-pole-double-throw (SPDT) transmit/receive (T/R) switch for 120 GHz wireless system in future work, which can be employed for the purpose of sharing a single antenna between the transmitter and receiver, thus leading to a more compact solution for fully integrated D-band systems in CMOS. Our target specifications for the proposed SPST switch at 120 GHz are an insertion

loss of <3 dB, an isolation of >15 dB, and input P_{1dB} of >10 dBm. The detailed target specifications for the 120-GHz SPST switch are given in Table I.

The proposed switch design is shown in Fig. 3, which is composed of the parallel-stripline swap hybrid coupler with DGS, two shunt nMOS transistors T_1 and T_2 , and two biasing resistors R_{G1} and R_{G2} at transistor gate terminals. The enhanced coupler's inductance is used to compensate the shunt parasitic capacitances that are introduced by the control transistors T_1 and T_2 . The transistors T_1 and T_2 are used to turn on or turn off the switch, depending on the state of the control voltage (V_{ctrl}). When V_{ctrl} is set to 0 V, both transistors T_1 and T_2 are off-state. Then, the signal at Port 1 can be passed to Port 2 through the coupler. When the V_{ctrl} is 1.2 V, both transistors T_1 and T_2 are on-state and thereby both ports are shorted to the ground. Ideally, there is no signal passing through from Port 1 to Port 2. The finger width of 2.5- μm and a minimum gate length of 60-nm are chosen for both transistors T_1 and T_2 to obtain the optimum compromise between isolation and insertion loss performance. The gate resistors R_{G1} and R_{G2} are used to bootstrap the gate at RF. By bootstrapping the gate, it will be floating at RF and hence its gate-to-source and gate-to-drain potential will be relatively constant.

Fig. 3. Schematic of proposed SPST switch using parallel-stripline swap hybrid coupler with DGS.

The power-handling capability or linearity of the SPST switch is evaluated by the input 1-dB compression point (P_{1dB}), which is directly associated with the off-state shunt transistors. With large resistors R_{G1} and R_{G2} floating the gates of transistor T_1 and T_2 at RF, the voltage amplitude of the signal can be effectively increased to $2V_{th}$, where V_{th} is the threshold voltage of the nMOS transistor [10, 11]. Hence, the input P_{1dB} of switch with gate biasing resistor is derived in dBm [11] as:

$$P_{1dB} = 10 \log \left(\frac{2V_{th}^2}{|Z_{in}|} \right) + 30 \quad (1)$$

Where Z_{in} is input impedance. For the 65-nm bulk CMOS process, the typical value of V_{th} is around 0.5–0.6 V, thereby the calculated input P_{1dB} is around 10–11.6 dBm for $Z_{in} = 50 \Omega$. As illustrated in Fig. 4, input P_{1dB} is enhanced with the increasing of R_G until R_G is higher than 100 Ω where P_{1dB} is almost constant due to the turn-on of the junction diodes.

Larger gate biasing resistor provides better DC isolation on the gate and improves switch linearity, but at the expense of longer switching times because the gate capacitance must be charged and discharged through high resistance values of gate biasing resistor. A typical range of values for gate biasing resistor is 5 k Ω to 15 k Ω . Fig. 5 shows the detailed rise time t_r (from 10% up to 90% of the maximum output swing) and fall time t_f (from 90% down to 10% of the maximum output swing) of the output signal when both gate biasing resistors R_{G1} and R_{G2} increase from 6 k Ω to 14 k Ω . The switch output voltage takes longer time to reach its maximum value for larger R_G . The switching speed could be improved by decreasing gate bias resistors R_{G1} and R_{G2} . To tradeoff between input P_{1dB} and switching response speed performance, the resistance value of R_{G1} and R_{G2} is chosen to 10 k Ω .

Fig. 4. Input referred P_{1dB} compression point as function of the changes in the values of the gate resistor (R_G).

Fig. 5. Switching speed performance as function of the changes in the values of the gate resistor (R_G).

The cross-section schematic of the 65-nm bulk CMOS process is illustrated in Fig. 6(a). From bottom to top, this process includes one polymer layer, seven thin metal layers (M_1 through M_7) and two thick metal layers (M_8 and M_9). Note that the fat-wire of M_8 can achieve lower loss than M_9 although M_9 is higher than M_8 from the substrate, because M_9 is aluminum while the other metal layers are copper. This technology provides two opinions of nMOS transistors, thin gate for the 1.2 V

supply voltage and thick gate for a 2.5 V supply voltage, respectively. The nMOS transistor for low-power applications achieves a cutoff frequency f_T around 200 GHz and a maximum oscillation frequency f_{MAX} around 220 GHz, respectively. The thickness, dielectric constant and resistivity of the substrate are 737 μm , 11.9 and 1.5 $\Omega\cdot\text{cm}$, respectively.

In order to achieve more accurate performance of the switch, a 3-D physical model of the SPST switch that included the whole passive components is built in a 3-D full wave electromagnetic (EM) high-frequency structure simulator (HFSS), as plotted in Fig. 6(b). The coupler is implemented by using sub-top layer (M_8) as the transmission line and bottom layer (M_1) as the ground plane, as well as two square vertical metal vias. The T type junction of T_1 and T_2 are used to connect to the drain of two shunt nMOS transistors T_1 and T_2 . In this work, the design parameters including all passive components and interconnections are optimized using 3-D EM HFSS simulator and circuit co-simulations, which are depicted in Fig. 3 & 6.

Fig. 6. (a) Cross-section schematic of the 65-nm bulk CMOS process; (b) The 3-D model of the SPST switch.

3 Measurement and discussion

The proposed SPST switch was fabricated using 65 nm bulk CMOS technology. The die microphotograph of the fabricated SPST switch is shown in Fig. 7. The whole chip occupies a silicon area of 0.0418 mm^2 including all testing pads with a core size of only 0.0036 mm^2 . Note that the die thickness is about 0.767 mm.

Fig. 7. Die microphotograph of the proposed SPST switch.

On-wafer measurements of two-port S -parameters were performed from 110 to 170 GHz using Cascade Microtech Elite 300 probe station with Cascade 50- μm pitch ground-signal-ground (G-S-G) waveguide probes, Agilent N5247A PNA-X Microwave Network Analyzer and two 110–170 GHz VDI's frequency extension modules. The system is calibrated using a short-open-load-thru (SOLT) probe-tip calibration technique on a Cascade Impedance Standard Substrate. The measured results are de-embedded using the thru de-embedding technique [12] to mitigate the effects of the interconnections and testing pads.

Fig. 8. Simulated and measured ILs and ISOs for the SPST switch.

Fig. 9. Simulated and measured RLs for the SPST switch.

The simulated and measured ILs curve are plotted in Fig. 8(a). It can be seen that the switch has a minimum measured IL of 1.6 dB (1.4 dB simulated) at 110 GHz. The measured IL is 1.9 dB (1.72 dB simulated) at 120 GHz. The switch exhibits a broadband characteristic and the measured IL is less than 3 dB from 110 to 134 GHz (110 to 139 GHz simulated). The simulated and measured ISOs between Port 1 and Port 2 are shown in Fig. 8(b). The measured switch achieves a maximum ISO of 17 dB (18.3 dB simulated) at 110 GHz. The measured ISO is better than 15.0 dB (17 dB simulated) from 110 GHz to 150 GHz. The simulated and measured RLs are presented in Fig. 9. The measured RL is better than 10 dB (14 dB simulated) from 110 GHz to 140 GHz. The measured RL is approximately 2 to 4 dB worse than the simulations at the frequency range of 110 to 140 GHz.

The discrepancies between measured results and simulated results may be mainly due to the existence of the randomized dummy metallization which had not been fully considered in the initial simulation because of limited computing resource. These dummies metallization introduced additional parasitic capacitance, which affected the flow of ground current along DGS perimeter, as well as the inductance and Q factor of the coupler. As the consequences, the RL and ISO are worse than the simulation results. When input and output matching is degraded, the measured IL also becomes worse.

The power-handling capability P_{1dB} is not measured at 120 GHz due to power limitation of our available testing facilities. Because the maximum output power from frequency extension module is less than -10 dBm at D-band that was well below the input P_{1dB} of tested switch. The input P_{1dB} was simulated at 120 GHz for the SPST switch. The simulated input P_{1dB} is around 12.8 dBm at 120 GHz, as shown in Fig. 10. The calculated input P_{1dB} is around 11.3 dBm when the value of V_{th} and V_{ctrl} are 580 mV and 0 V, respectively. The difference between simulated and calculated input P_{1dB} is mainly due to the input impedance is less than $50\ \Omega$ when the input matching network is degraded because of the existence of randomized dummy fills.

Fig. 10. Simulated input P_{1dB} for the SPST switch.

The switching speed of the SPST switch is simulated by employing an input sinusoid signal at 120 GHz, as well as a 500-MHz pulse control signal of 50% duty-cycle. The rise time t_r and fall time t_f of the output signal are 0.43 ns and 0.35 ns, respectively, as shown in Fig. 11.

Fig. 11. Simulated switching speed performance.

The performance of the proposed SPST switch is summarized and compared with recently reported D-band SPST switches in Table II. Compared with the other switches, this SPST switch exhibits competitive performance, especially in terms of insertion loss and core area. Note that the proposed SPST switch is used to realize SPDT T/R switch for TDD-based wideband front-end in the future work rather than realize the on-off keying (OOK) modulation. Therefore, the switching speed is not the key target specification.

Table II. Comparison with recently reported D-band SPST switch

Reference	[3]	[4]	[5]	[6]	This Work
Process	150 nm GaAs	130 nm BiCMOS	65 nm CMOS	130 nm CMOS	65 nm CMOS
Freq. (GHz)	110–135	135	110–170	94	120
IL (dB)	4.1–5	4.7	2.5–3.6 [†]	3.8	1.9
RL (dB)	>10	16.3	>8.7	11	>10
ISO (dB)	>15	12.5	>19.5	20.1	>15.5
V_{ctrl} (V)	0/–2	0/2	0/1.2	0/2	0/1.2
P_{ldB} (dBm)	N.A.	6*	N.A.	N.A.	12.8*
Switching Speed (Gb/s)	N.A.	10	1	20*	0.5*
Core Area (mm ²)	0.6888	0.128	0.013	0.0676	0.0036

[†]estimated value from figures; *simulated

4 Conclusion

The proposed switch design using a parallel-stripline swap hybrid coupler with defected ground structure (DGS) was found to be more efficient in comparison to conventional TL, especially at the higher frequency. While the conventional TL fails to deliver low insertion loss at the high frequency, the equivalent capacitance introduced by the coupler gap leads to series resonance condition which results in lower insertion loss at the higher frequency. In addition, the use of DGS results in enhanced equivalent inductance to compensate the parasitic capacitance of the control transistor. Overall, the hybrid coupler provides more degree of design freedom since the capacitance and inductance can be tuned by the structural dimension of the coupler.

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