Design of a V-band Phase Shifter Using SP4T RF-MEMS Switches with Sonnet

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Abstract: This paper presents the design of a V-band switched-line phase shifter using SP4T RF-MEMS switches. Sonnet simulations are used to achieve accurate circuit models of both the RF-MEMS switches as well as CPW bends within the phase shifter. The V-band phase shifter utilizes two SP4T RF-MEMS switches to perform the delay line switching. The RF performance of the SP4T MEMS switch is optimized to address the challenge of developing high performance, broadband switches for emerging 60 GHz wireless applications. Full-wave Sonnet simulations are used to optimize the RF-MEMS switch topology to achieve low return-loss performance. The SP4T SONNET model is then used in the circuit simulation to analyze the performance of the RF-MEMS integrated V-band phase shifter. The experimental result shows less than 1° phase error at 60 GHz in comparison to the simulation results.

Keywords: RF MEMS, SP4T, SONNET, cantilever switches.

1. Introduction

With the maturing of radio frequency microelectromechanical systems (RF-MEMS) technology in the last ten years, there have emerged numerous applications using RF-MEMS technology at millimeter-wave frequencies including radar systems for defense applications, satellite communication systems, and terrestrial communication systems [1]. In particular, the 60 GHz band has attracted a great amount of research interest due to potential applications for indoor broadband wireless communications. However, 60 GHz applications face multiple challenges including high path-loss (10-15 dB/km) due to atmospheric oxygen and multipath effects due to the cluttered indoor environment. Adaptive beamformers are one of the promising solutions needed to effectively exploit this frequency band by generating the required radiation patterns for operating in such a complex environment.

Single-pole 4-throw (SP4T) RF-MEMS switches are important enabling components for low-loss broadband implementations of true-time delay phase shifters required to implement these beamformers. Most single-pole multi-throw (SPMT) switches developed thus far are built by surrounding the input with multiple SPST switches controlling the corresponding signal path. Despite the outstanding performance of the SPST switch on which they are based, these previously developed SP4T switches are all limited to below 50 GHz due to their relatively long spokes. This work presents the design of an SP4T MEMS switch using the cantilever RF-MEMS switch developed in [2] and a V-band 2-bit phase shifter with such SP4T switches integrated. The cantilever switch has dimensions of 75 μm by 30 μm. The switch is designed to be integrated into a 7/50/7 μm CPW line on a 500-μm thick quartz substrate.

2. Design of the SP4T RF-MEMS Switches

Most single-pole multiple-throw (SPMT) switches developed thus far are built by surrounding the input with multiple SPST switches controlling the corresponding signal path. The performance of the SPMT switch greatly depends on the performance of the SPST and the proximity with which the SPST switches can be arrange in relation to the central hub (see Fig.1). The topology of the central hub and the spokes connecting the switch and center hub generally introduce impedance mismatch and thus degrade the return loss performance of the SPMT switches. In order to minimize this mismatch in our design, we have used cantilever switches placed in series with the CPW transmission line. These series switches have an upstate capacitance of 2 fF resulting in an isolation of better than 15 dB up to 75 GHz. With an applied actuation voltage of 75 V, the insertion loss is less than 0.2 dB up to 20 GHz and less than 0.4 dB up to 50 GHz.

As shown in Fig. 2, a Sonnet model is constructed to enhance the understanding of the return loss performance of the SP4T switch shown in Fig. 1 and used in this work. In the downstate position, the actuated cantilever is represented by a metal strip suspended 1.25 μm above the circuit layer with via holes on both ends to connect the gap in the circuit. In the up-state position, the metal strip is suspended 1.25 μm over the central hub with a 5 μm by 30 μm overlap. Air bridges are also used in this design to equalize the CPW ground-planes. Air bridges are represented by a metal strip with via holes on both ends connecting the air-bridge to the CPW metal level. This type of design provides greater simplicity in the fabrication of the SP4T switches.

A general circuit representation of the SP4T switch that can be used for design optimization is shown in Fig. 3. In this generalized circuit, Z_s is the normalized characteristic impedance of the connecting spoke with an electrical length of θ, X_C and X_L are the normalized reactances introduced by the upstate capacitance and parasitic inductance of the switch, and R_C is the downstate contact resistance of the switch. X_C, X_L, and R_C are parameters determined by the SPST switch on which the SPMT is based.

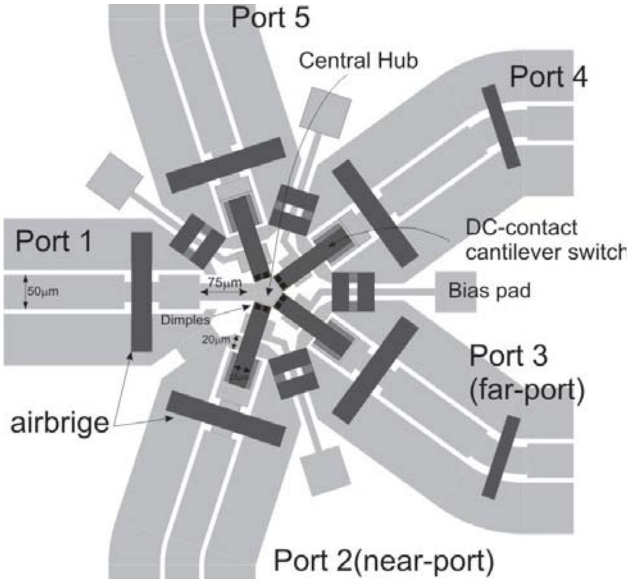


Fig.1. The designed layout of SP4T RF MEMS switches.

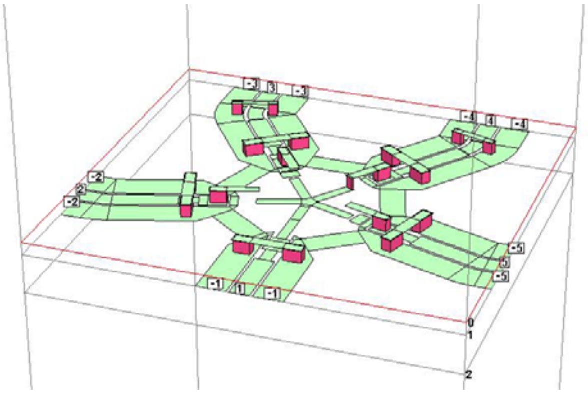


Fig. 2. The 3D SONNET representation of the SP4T RF-MEMS switch.

The electrical length of the spoke, θ, is primarily restricted by the footprint of the SPST and the characteristic impedance Z_s can be adjusted to achieve a better impedance match by changing the transverse dimension. In Fig. 3, port 5 is actuated and each external port is terminated with a matched load.

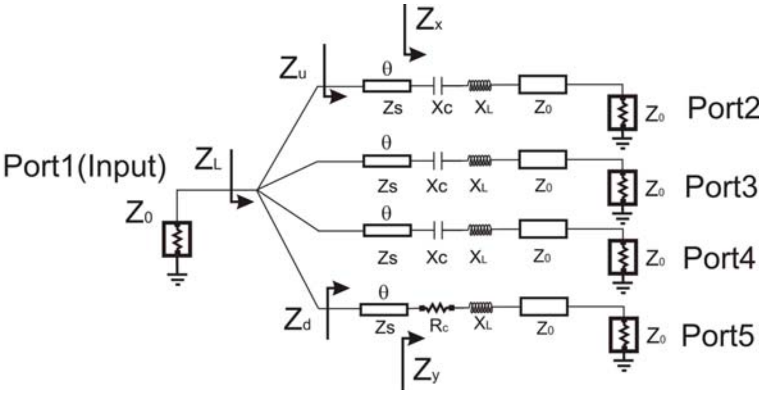


Fig. 3. A general equivalent model of the SP4T switches design.

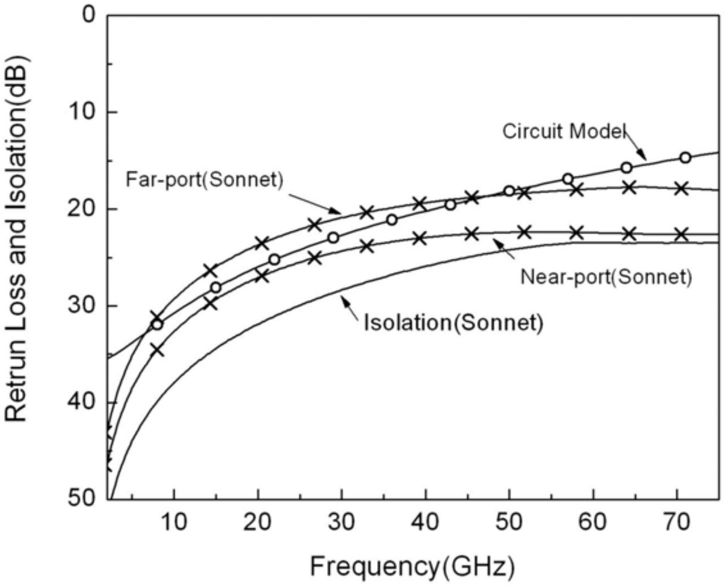


Fig. 4. Simulated performance of SONNET model and an equivalent circuit model.

The Sonnet simulation results, as shown in Fig. 4, indicate that the near-port (port 2) of the SP4T has better return loss performance than the far-port (port 3). The return loss performance predicted by the equivalent circuit model shown in Fig. 3 reasonably matches the far-port full-wave simulation. However the discrepancy in the near-port results is believed to be due to the coupling between the input and near-port which induces a better impedance match. While the topology difference between the near-port and far-port effects the return loss, the isolation of both ports shows little difference due to the small up-state capacitance and the Sonnet simulations match very well with the circuit simulation. The simulated S-parameter performance of the SP4T switch shows a return loss better than 18 dB and isolation better than 20 dB up to 65 GHz.

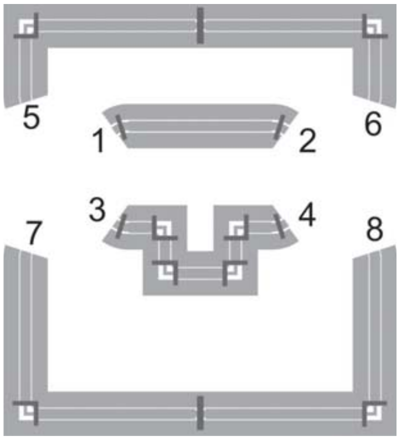
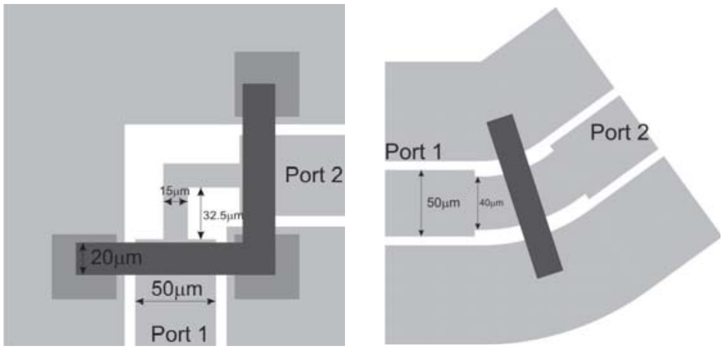


Fig. 5 The phase shifter delay line topology.

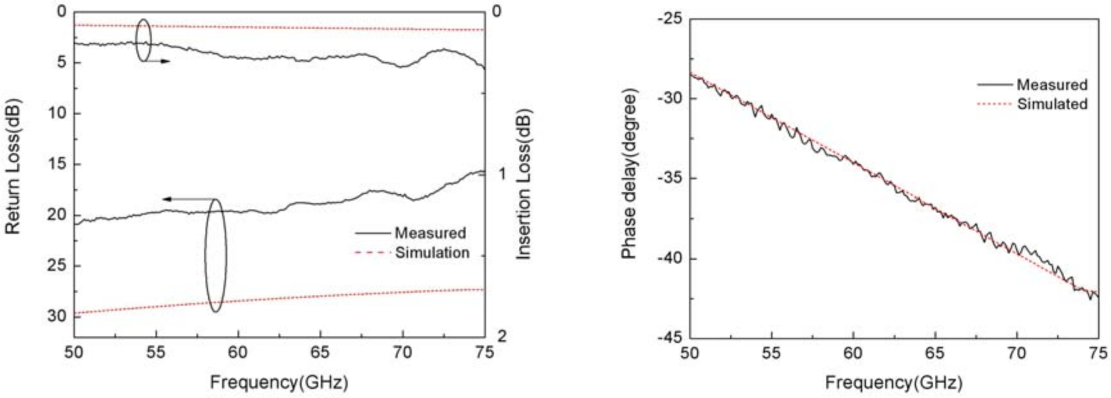


(a) (b)

Fig. 6. Layout of the (a) 90° and (b) 36° bend.

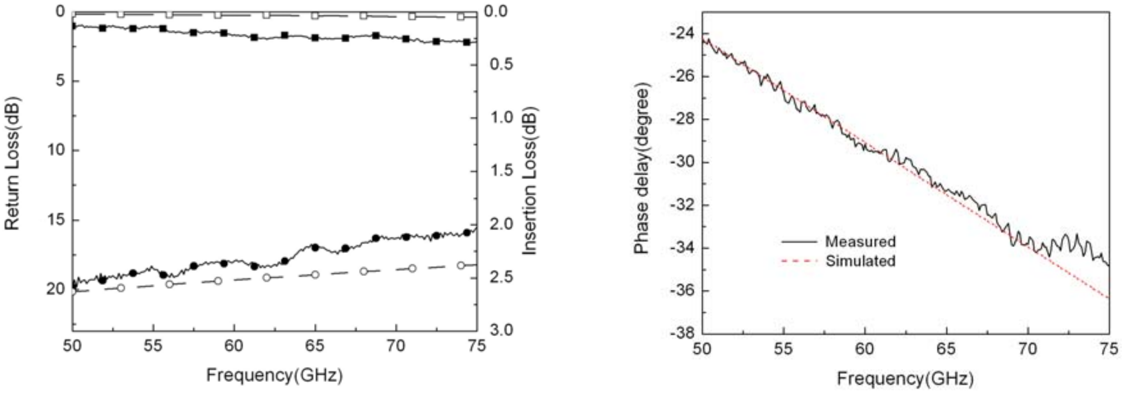
3. V-band Phase Shifter

A V-band 2-bit phase shifter is designed with three delay lines providing 90°/180°/270° phase shift in relation to the reference line at 60 GHz as shown in Fig. 5. These four delay lines are connected to the input and output using two SP4T RF-MEMS switches. While in operation, each phase delay path is chosen by actuating the corresponding two throws. In order to achieve a compact design with minimum phase error, the reference path is chosen to be 556 µm (electrical length: 43°@ 60 GHz). This allows four 90° CPW bends to fit in-between the two SP4T switches to form the 90° delay path with little transmission distortion caused by intra-coupling in the meandering lines. Two 36° CPW bends are configured to connect the SP4T switches to the reference and 90° delay lines. The 90° CPW and 36° bends in this work use the standard design described in [2]. Air-bridges are used in CPW based circuits to suppress the parasitic slot-line mode. The layout of the 90° and 36° CPW bend are shown in Fig. 6. The S-parameter performance of the 90° and 36° CPW bends are simulated using Sonnet and is plotted along with the measurement results in Figs. 7 and 8. Although the measured insertion loss and return loss



(a) (b)

Fig. 7. Measured and Simulated (a) S-parameter performance and (b) phase delay of the 90° CPW bend.



(a) (b)

Fig. 8. Measured and Simulated (a) S-parameter performance and (b) phase delay of the 36° CPW bend.

performance are worse than the simulation results, both bends demonstrate a return loss better than 17 dB and insertion loss less than 0.3 dB in the band of interest. More importantly, the phase delay of both bends matches the measured results to within <1° across the band from 50 to 75 GHz.

The delay network comprising four delay lines is simulated using transmission-line models in ADS and using the 90° and 36° bend data obtained with Sonnet. The results are combined with the SP4T simulation results acquired with Sonnet to predict the performance of the four phase states. The simulation results, as shown in Fig. 9, predict that the return loss of the phase shifter is better than 13 dB from 55 GHz to 65 GHz. The insertion loss of the network ranges from 2 dB to 2.7 dB depending on the phase state. In the simulation, the contact resistance of the MEMS switches is set to 1 Ω and the conductivity of the circuit line is set to 1.2×10^7 S/m for metal loss. This conductivity value is obtained by matching the measured transmission line attenuation (4.5 dB/cm @ 60 GHz). Fig. 9(b) shows the measured and simulated phase response for each phase state of the switched-line phase shifter. Due to accurate simulation, the measured response is within 1° of the predicted response at 60 GHz for each phase state.

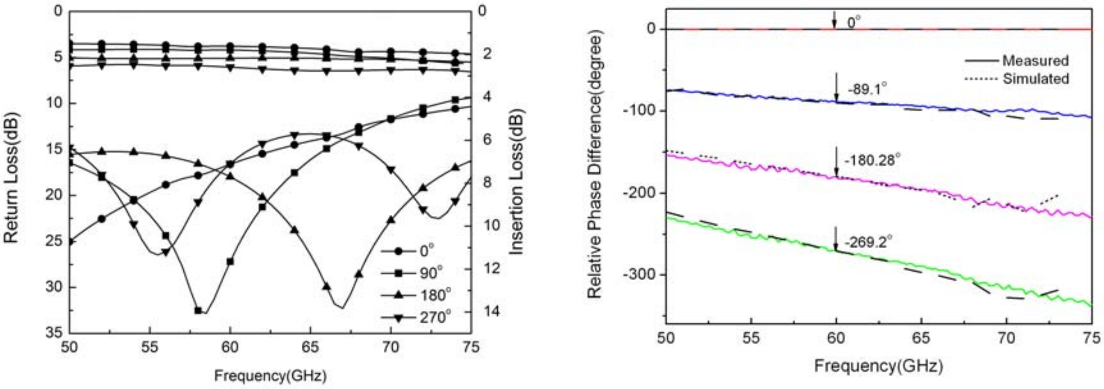


Fig.9. (a) Simulated return loss and insertion loss performance (b) Simulated and measured phase response of the V-band phase shifters.

4. Conclusions

A V-band switched-line phase shifter using SP4T RF-MEMS switches is designed with Sonnet. The simulation predicts outstanding return loss performance for the SP4T switches and V-band phase shifter with better than 13 dB from 55 to 65 GHz. Through the judicious use of both Sonnet and circuit simulations, an accurate simulation of the phase shifter circuit is obtained with the resulting measured phase error less than 1° at 60 GHz across all four phase states. Full-wave simulations using Sonnet are shown to be of great importance to the design and optimization of millimeter-wave components. They include the more pronounced coupling effect in millimeter-wave systems due to their generally compact footprint. Full understanding of the designed circuit and switching component performance thus can be achieved, bridging the gap between simulations and measurements to better serve performance budgeting and integration on a system level.

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