# 14GHz MEMS 4-bit Phase Shifter on Silicon

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***Abstract*—In this abstract we describe the work in progress on a 4-bit coplanar waveguide (CPW) MEMS phase shifter simulated, fabricated, and measured at 14 GHz on 400 µm high-resistivity silicon ($\varepsilon_r$ = 11.7). Simulated results using a full wave simulator predict a return loss better than -19 dB and isolation better than -0.1dB for a one bit phase shifter using perfectly conducting lines. Measurement results for single MEMS switches have shown -22 dB return loss and -0.095 dB isolation in the UP (not activated) state and -0.83 dB return loss and -14.5 dB isolation in the DOWN (activated) state. It has also been shown that the single bit phase shifters exhibit accurate phase shifts, but higher than expected loss.**

***Index Terms*—MEMS, phase shifter, multi-bit, switches.**

## I. Introduction

MICROELECTROMECHANICAL systems (MEMS) are quickly becoming a low-cost, high-performance replacement for solid-state switches (FETs, PIN diodes, etc.). Multi-bit phase shifters have been around for several years and have a common application in phased array antenna systems. The combination of the two technologies is the purpose for this project. Furthermore, a phase shift step size of 22.5$^o$ is desired, which requires a 4-bit phase shifter. Most current phase shifters max at 3-bits, although 4-bit shifters have been published on other substrates (i.e. glass, GaAs), using solid-state switches (i.e. JFETs, PIN diodes), and using other line types (i.e. microstrip) [1-3]. This project is the first 4-bit on silicon using MEMS switches, which furthers the state of the art. Measurement results of the single MEMS switch and of the 1-bit shifters, which are simply cascaded to achieve a 4-bit shifter, are presented in this paper.

## II. Circuit Design and Fabrication

### A. Circuit Design

To achieve a 4-bit phase shifter, four 1-bit phase shifters must be designed. These four shifters share a common reference line length and have a relative phase difference of 22.5$^o$, 45$^o$, 90$^o$, and 180$^o$. There are sixteen possible states ranging from 0$^o$ to 337.5$^o$ with 22.5$^o$ steps. Each 1-bit shifter requires two sets of two cantilever MEMS switches, which are spaced λ/4 from the T-junction. This is shown as a 4-bit cascaded configuration in Figure 1.

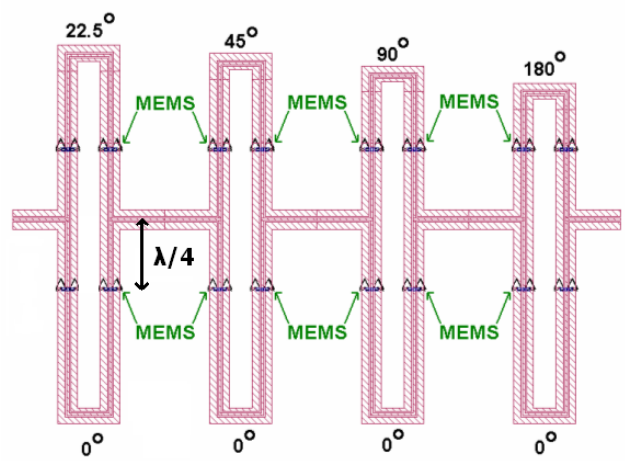


Fig. 1. Layout of 4-bit Phase Shifter.

Each set of MEMS is either in an UP (no activation) or DOWN (activation) state. When in the DOWN state, the MEMS bridge shorts the signal line to ground and effectively creates an RF open circuit. This causes the signal to flow through the opposing path. By choosing the set of MEMS to activate, the signal can be driven through the reference path or the delay path. A thin silicon nitride ($Si_3N_4$) layer is used to reduce stiction between the bridge and metal layer and also to isolate the DC activation voltage.

Simulation results for the 1-bit phase shifter are summarized in Table I.

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TABLE I
SIMULATION RESULTS FOR ONE-BIT PHASE SHIFTER
(USING SONNET FULL WAVE SIMULATOR)

| Expected Phase | Magnitude S11 | Magnitude S21 | Phase S21 | Phase Error |
|---|---|---|---|---|
| 22.5° | -19.06 dB | -0.094 dB | 21.363° | 1.137° |
| 45° | -24.485 dB | -0.074 dB | 52.518° | 7.518° |
| 90° | -25.465 dB | -0.021 dB | 88.171° | 1.829° |
| 180° | -20.773 dB | -0.077 dB | 178.332° | 1.668° |

The size of the 4-bit phase shifter is approximately 16.5 mm by 8 mm. This is comparable to the size of a U.S. dime, as shown in Figure 2.

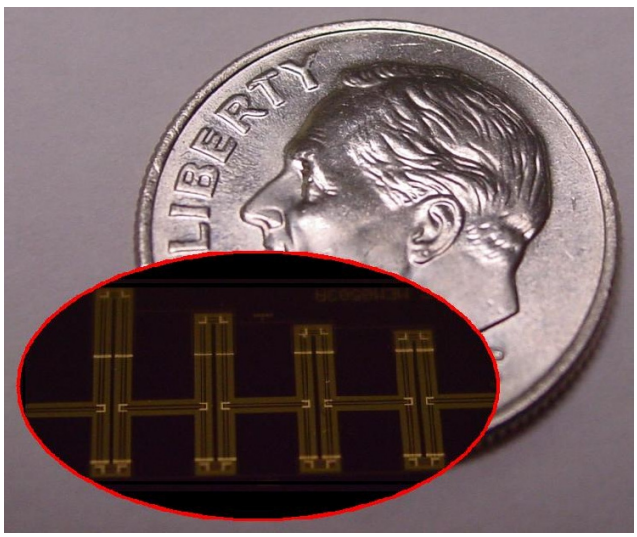


Fig. 2. Size Comparison of 4-bit Phase Shifter to a United States Dime.

### B. Fabrication

Preliminary fabrication of the MEMS switches, the 1 bit, and the 4-bit phase shifters has been completed. A detailed look at the cantilever MEMS switch and T-junction air bridge is shown in Figures 3 and 4.

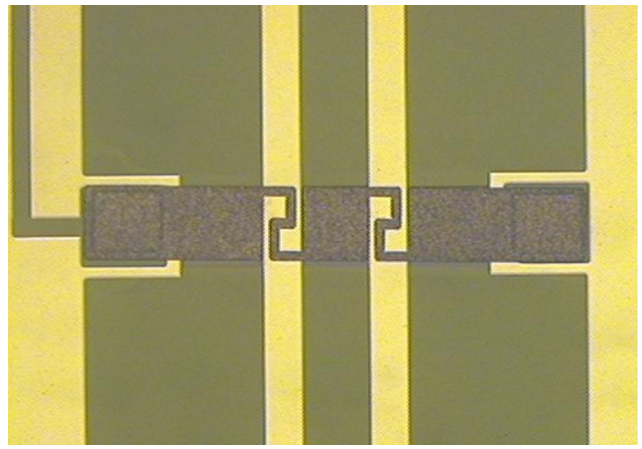

Fig. 3. Single Capacitive MEMS Switch.

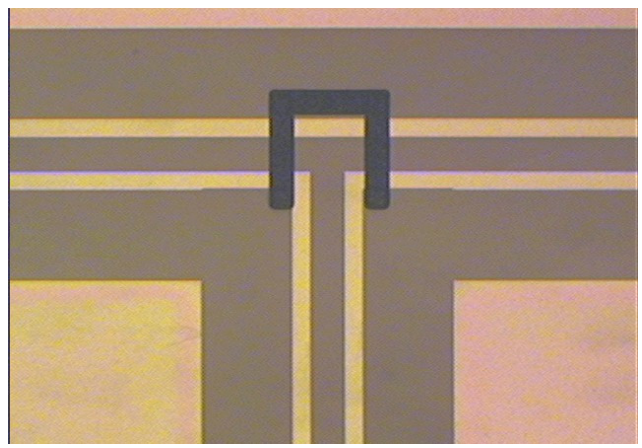

Fig. 4. T-Junction Air Bridge to Cancel Slot Line Modes.

## III. MEASUREMENTS

The measurement results for the MEMS switch in the UP state are shown in Figure 5.

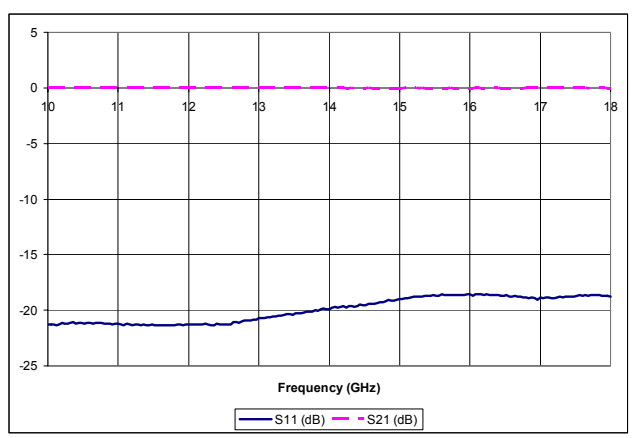


Fig. 5. MEMS Switch in the UP State.


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Measurement results for the MEMS switch in the DOWN state are shown in Figure 6.

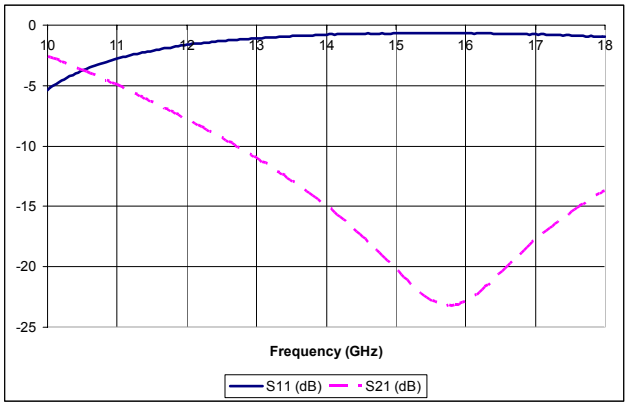


Fig. 6. MEMS Switch in the DOWN State.

The loss associated with MEMS switches is far less than the loss exhibited by their solid state counterparts (such as pin diodes, which can exhibit several dB of loss).

The measurement results for the 1-bit phase shifter are summarized in Table II.

TABLE II
MEASUREMENT RESULTS FOR ONE-BIT PHASE SHIFTER

| Expected Phase | Magnitude S11 | Phase S21 | Phase Error |
|---|---|---|---|
| 22.5° | -5.1257 dB | 25.697° | 3.197° |
| 45° | -16.35 dB | 54.906° | 9.906° |
| 90° | -10.787 dB | 95.101° | 5.101° |
| 180° | -10.886 dB | 177.88° | 2.200° |

It is expected that the more bits in a phase shifter, the greater the overall loss will be. This is due mostly to metal and substrate losses. Even though the overall length of the 4-bit phase shifter is about 16.5mm, the signal path length ranges from 36.5 mm (for the 0° case) to 46.1 mm (for the 337.5° case). Using Thru-Reflect Line (TRL) calibration, 0.8-1.2 dB/cm loss was observed over the frequency range. This adds 3 to 5 dB of loss alone. Adding several more decibels of loss from the switches would not be acceptable, which is why the low-loss and high isolation characteristics of MEMS switches makes them ideal for multi-bit phase shifters. Expected measured results for the 4-bit phase shifter have been extrapolated and summarized in Table III.

TABLE III
SAMPLE OF EXTRAPOLATED RESULTS FOR FOUR-BIT PHASE SHIFTER

| Expected Phase | Magnitude S21 |
|---|---|
| 0° | -3.718 dB |
| 90° | -3.922 dB |
| 180° | -4.122 dB |
| 270° | -4.327 dB |
| 337.5° | -4.487 dB |

The measured phase shifts are generally within a few degrees of the simulated values. The loss is greater than expected which is suspected to be caused by slot line modes propagating through the coplanar waveguide. These modes are not being fully canceling out by the air brides. As the fabrication process is optimized, these slot line modes will be greatly reduced while maintaining a desired phase shift. In addition, a greater yield on the MEMS switches will be achieved and measurement results for the 4-bit shifter, which requires 16 working MEMS switches to measure, will be presented.

## IV. FUTURE WORK

Thus far, working 1-bit phase shifters at 22.5°, 45°, 90°, and 180° have been achieved. Attention will be given to improving the return and insertion loss. Optimization of the fabrication process will allow for measurement of the 4-bit phase shifter,

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