X-Band RF MEMS Phase Shifters for Phased Array Applications

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Abstract— In this letter, development of a low-loss radio frequency (RF) microelectromechanical (MEMS) 4-bit *X*-band monolithic phase shifter is presented. These microstrip circuits are fabricated on 0.021-in-thick high-resistivity silicon and are based on a reflection topology using 3-dB Lange couplers. The average insertion loss of the circuit is 1.4 dB with the return loss >11 dB at 8 GHz. To the best of our knowledge, this is a lowest reported loss for *X*-band phase shifter and promises to greatly reduce the cost of designing and building phase arrays.

Index Terms— Low loss, microelectromechanical systems (MEMS), phase shifters, switches.

I. INTRODUCTION

LOW-LOSS radio frequency (RF) microelectromechanical (MEMS) switches have been demonstrated by a number of research groups [1]–[4]. The next challenge has been in designing and fabricating monolithic integrated phase shifters that use the RF MEMS switches. While RF MEMS devices have switching speed inherently slower than GaAs transistors or p-i-n diodes, the devices offer lower loss and resistance and allow smaller designs that offer novel and practical solution for space-based phased arrays [5].

A number of topologies are available to shift phase. Switched line and loaded line designs require distributed line lengths and tend to be large at *X*-band [5]. Another way to achieve phase shift is by switching low-pass and high-pass filter elements, which typically requires large monolithic inductors. An alternate topology, and the one used for this design, is a reflection phase shifter. It is smaller, has wide-band response and is well suited for RF MEMS switch geometry.

II. CIRCUIT DESIGN

To attain our goals, a reflection phase shifter topology was chosen. We used microstrip construction on 0.021-in-thick high-resistivity silicon. The conductors were made of 4-μm-thick sputtered gold. The switches have on-capacitance of 3 pF and off-capacitance around 35 fF. Switching time is in 5-μs range. Construction and further switch details are described in [3]. The circuits require no quiescent current and thus dissipate very little power. The reflection topology requires only shunt switches, requires no matching networks, and uses Lange couplers, resulting in ultra low-loss wide-band performance.
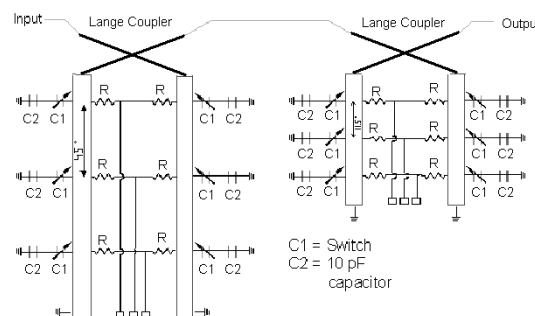
Fig. 1. Representation of two 2-bit phase shifter sections that form a 4-bit circuit.

Reflection topology requires half the transmission line length of the traditional switched line designs for phase shifting.

Fig. 1 shows a representation of a 4-bit reflection phase shifter. The circuit consists of two 2-bit reflection sections. The first 2-bit section is designed to shift the long states: 0, 90, 180, and 270°. The second 2-bit section shifts the short states: 0, 22.5, 45, and 67.5°. These two sections combine to produce a 4-bit phase shifter switching from 0 to 337.5° in 22.5° steps.

The operation of the design is simple. The RF signal is divided in the Lange coupler, propagating through coupled and direct ports down a 450-μm-wide transmission line. The impedance of the line does not have to be 50 Ω. As long as the reflection seen by the coupler is balanced from both ports, signals add in phase and no signal is reflected back to the input. The signal propagates through the delay lines and reflects from an actuated shunt switch or a shorted line at the end if all the switches are unactuated. Thus the switches, when actuated, provide RF shorts. If the reflected short at both ports is the same, the signals add in-phase and appear at the output of the Lange coupler. The phase reference, or 0°, is established when the first two switches shorting the delay lines are actuated. In the longer 2-bit section subsequent switches are separated by line length equivalent to 45° phase shift at 10 GHz, so the signal propagates 45° to the next shorted switch, reflects from it, and thus provides a total of 90° phase shifts. In the case of the longest state, the switch is unnecessary since the end of the line can be shorted directly at the end and provides the RF ground. Thus the 270° phase shift is obtained when all switches are unactuated and RF signal reflects from the short at the end of the transmission line.

The coupler is most critical part of the design. The tolerance of conductor widths and spaces must be controlled to within
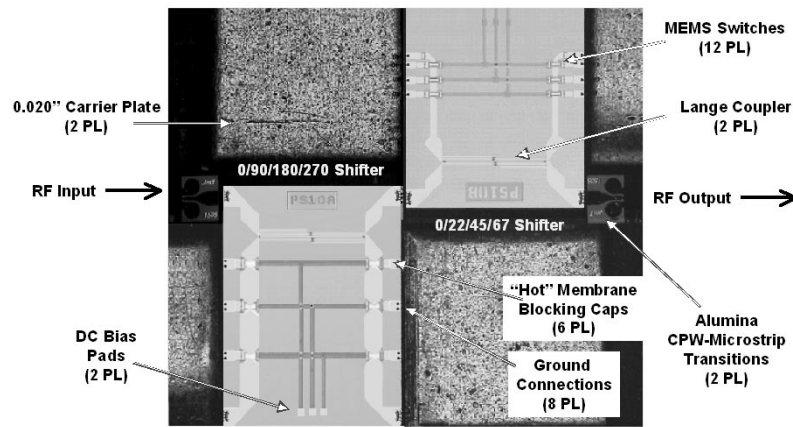
Fig. 2. Photograph of assembled 4-bit circuit.

a few microns for proper operation, otherwise the mismatch losses become significant and can easily reach 0.5 dB. Lange couplers are also quite large at *X*-band and set the width of the chips. They are also the most lossy circuit elements, measuring ∼0.5-dB insertion loss each.

The switches are in "hot membrane" configuration, meaning that the voltage is applied to the membrane rather than to the transmission line. This eliminates possibility of creating an inversion channel in the silicon substrate, which may substantially degrade RF loss characteristics. Since the switches require negligible current, RF–DC decoupling is achieved with 10-k-Ω resistors. A 10-pF blocking capacitor isolates the switch control voltage from the ground connection.

The shorter 2-bit section functions the same except the phase shift between the switches is 11.25° and the transmission line is 130 μm wide, the same width as electrodes of the switches. The signal travels 11.25°, sees RF short, reflects back 11.25 °, and thus results in 22.5° phase shifts. The longest state again needs no switch as the transmission line is shorted at the end. The smaller bits are more difficult to achieve as the phase shifts are small and switches tend to bunch together. A small series capacitor was placed in the longest state past all the switches. Its reactance reduces the phase shift, allowing us to make the line physically longer than 11.25° for layout constraints. The switches were also scaled smaller to alleviate parasitic coupling.

III. CIRCUIT ASSEMBLY AND RESULTS

The photograph in Fig. 2 shows an assembled 4-bit phase shifter circuit. The assembly of the circuit requires all grounds to be bonded in since vias are not available. Thus all lines that require grounding terminate at the chips' edges. The devices are mounted on gold plated Kovar carrier plates with conductive epoxy. Coplanar waveguide to microstrip transitions are also mounted with the epoxy and are ribbon welded to the input and output to facilitate semi-automated probing. Since the substrate thickness is 21 mils, to reduce ground inductance from bonding 21 mils down to carrier plate, small carrier plates 20 mils thick are mounted on the grounding sides of the chips. The resulting bonds are less than 0.005 in long and cause no problems.
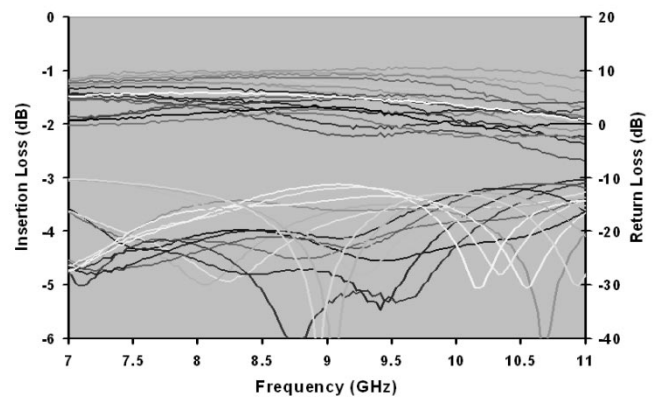

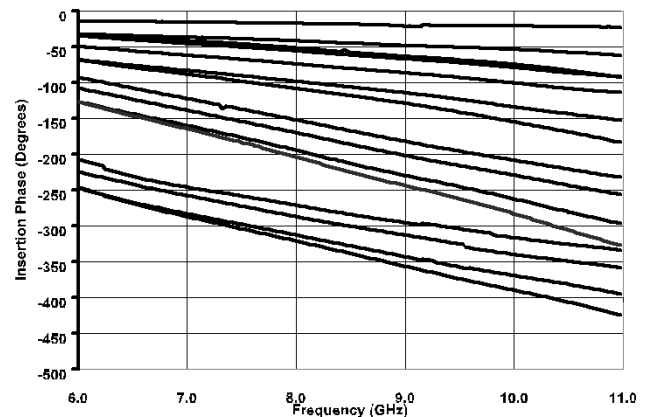Fig. 3. Insertion loss and return loss of the 4-bit *X*-band phase shifter.

Fig. 4. Phase performance of the 4-bit *X*-band phase shifter.

The measurement of the circuits was accomplished using Cascade-Microtech Summit 10 000 probe station with a Wiltron37369A network analyzer. Control voltages of 35–40 V were supplied with standard 15-pin probe cards.

Figs. 3 and 4 show the insertion loss and return loss, and phase performance of a 4-bit circuit, respectively. The average insertion loss was 1.4 dB at 8 GHz, with loss of 1.7 dB over >30% bandwidth. The return loss was >11 dB for all 16 states. The variability from chip to chip was within 0.3 dB and

at higher frequencies was caused by mismatch loss occurring because of the assembly variability. Phase performance at 10 GHz was within half the least significant bit, except for the 180 and 270° sections, which were somewhat long. The phase error was caused by parasitic capacitance between the switch posts and transmission lines and can easily be fixed by shortening the line lengths.

Further improvements are expected. Since the couplers are responsible for roughly 60% of total loss, off chip couplers will be designed on alumina substrate and integrated with silicon chips. Alumina couplers are expected to have 0.2 dB less loss than the ones built on silicon. Via technology on silicon is also being pursued to make the assembly simpler and to reduce the circuit size.

IV. CONCLUSIONS

Radio frequency MEMS *X*-band 4-bit phase shifters have been designed, fabricated, and tested. The circuits will shift phase from 0 to 337.5° in 22.5° steps when corrected for the encountered parasitics. The insertion loss of the devices measured at 1.4 dB. To our knowledge, this is the lowest loss ever reported. More improvements are being currently investigated that are expected to reduce the insertion loss of the 4-bit circuit to 1.0 dB.

ACKNOWLEDGMENT

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