A 2-Bit RF MEMS Phase Shifter in a Thick-Film BGA Ceramic Package

K. Varian and D. Walton

***Abstract*—The development of a thick-film hermetic BGA package for a radio-frequency (RF) microelectromechanical systems (MEMS) 2-bit phase shifter is presented. The measured packaged MEMS phase shifter average in-band insertion loss was 1.14 dB with an average return loss of 15.9 dB. The package transition insertion loss was less than 0.1 dB per transition with excellent agreement between simulated and measured results. It was also demonstrated that the RF MEMS phase shift performance could be improved to obtain a phase error of less than 3.3 degrees. The first reported measurements of the average rise and fall times associated with a MEMS circuit (in this case a 2-bit phase shifter) were 26 and 70 μs, respectively. The advent of packaged RF MEMS phase shifters will reduce the cost (both design and building) of future phase arrays.**

***Index Terms*—Ball grid arrays, micromechanical devices, packaging, switching circuits.**

I. Introduction

TWO of the main advantages of radio-frequency (RF) microelectromechanical systems (MEMS) are performance and cost. Today's MEMS MMICs have demonstrated outstanding performance [1]–[3] and the developmental steps indicate that die cost targets are obtainable. The next major step in preparing this technology for system applications is packaging. The packaging challenge is particularly difficult for MEMS devices since the insertion loss of the circuits is very low, on the order of 1 dB. Several recently published papers [2], [4], [5] on RF MEMS switches address packaging. Papers [2], [4] address a lateral interface. In the first paper, the RF transition to outside the package is under a glass sidewall and the later is a micromachined channel that is subsequently filled with dielectric under a metallic seal ring. The increased packaging losses are associated with the line transition under the wall and the increase in line length. At the next level of assembly, there is an added "system" cost of additional space for the leads. Paper [4] addresses vertical interconnects, but contact is made to the backside by way of a coplanar structure. Fig. 1 illustrates the packaging approach chosen, Ball Grid Array (BGA). The package utilizes the vertical dimension to minimize the package footprint and a straight forward vertical attachment at the next level, thus minimizing the transition length and RF loss. This paper will demonstrate a BGA package with an insertion loss of less than 0.1 dB per transition, a small system footprint, and a potentially low cost.

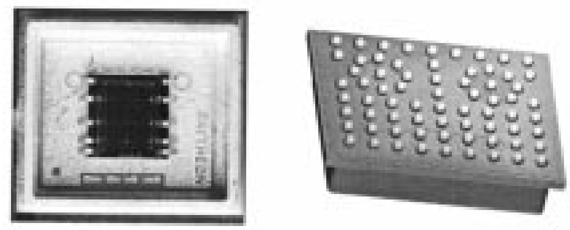

Fig. 1. Picture of packaged assembly and pictorial representation of the backside.

Some of the challenges addressed by this packaging approach were return loss, hermeticity, and the physical requirements of the RF MEMS circuits. Hermetic packaging was required to protect die from mechanical damage, moisture, and other environmental factors. RF MEMS switches present an additional packaging constraint, since the resulting package must allow the RF MEMS switch membranes the freedom to move. This means that some of the common packaging techniques used with semiconductors, such as potting, cannot be used. The packaging challenges, approach, and design will be discussed in the following section followed by the results and conclusion sections.

II. Design

The phase shifter, RF MEMS switches, and circuit are described in [1], [3], with a summary description following. The phase shifter utilized a reflection topology with microstrip lines, Lange couplers, and RF MEMS switches on 0.021–in high resistivity silicon. The conductors were made of 4 μm thick sputtered gold. The RF MEMS switches were capacitive shunt membrane switches. The switches had an on capacitance of 3 pF and an off capacitance of around 0.035 pF. The 2-bit phase shifter has an average in-band, 8 to 10 GHz, insertion loss of 0.96 dB, and an in-band return loss of greater than 14 dB, as shown in Fig. 2.

The package, Fig. 1, used a thick-film substrate to which a ring frame with a seam-sealable lid was brazed and solder balls were attached. The thick-film substrate was 0.020-in thick alumina. The 0.006-in diameter vias were used to conduct the signal and dc between the top and bottom surfaces. A conventional alloy 46 ring frame and alloy 48 seam-sealed lid were attached to the top surface to provide a hermetic package. To ensure via hermeticity (1×10^{-7} ATM-cc/s or greater) and to restrict the flow of solder associated with the solder ball attachment process, a glass layer was added to the backside. The weight of the completed BGA assembly was approximately 1 g.

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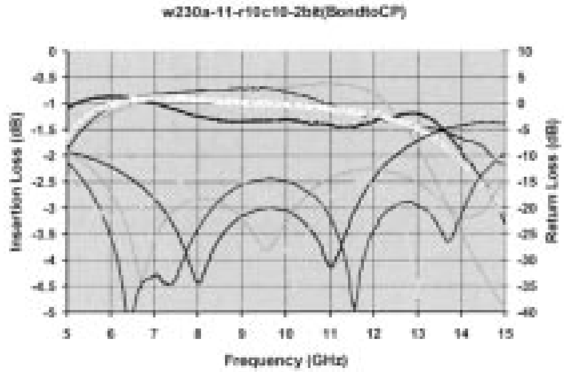

Fig. 2. Response of RF MEMS phase shifter, bare die.

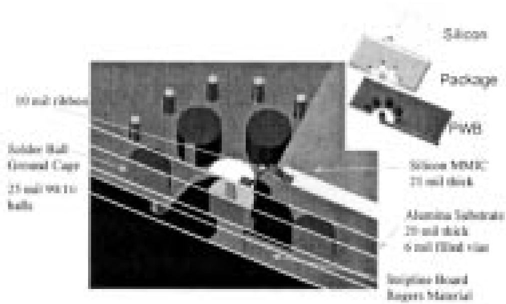

Fig. 3. Model used in the simulation of the transition.

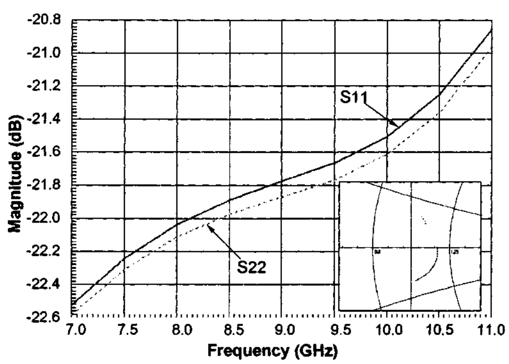

Fig. 4. Predicted response of the transition.

The transition, as pictorially shown in Fig. 3, from the silicon MEMS die through the alumina substrate to the solder balls was simulated with the e-m simulator HFSS (Ansoft's high frequency structure simulator). The predicted results are better than a 21 dB return loss across the desired band, as shown in Fig. 4. The simulated transition performance was then added to an advanced design system (ADS) model for the module with typical measured s-parameters for the MEMS die. The predicted module average insertion loss was 1.28 dB.

III. Results

The measured module performance had an average in-band insertion loss of 1.14 dB (see Fig. 5) and an average return loss of 15.9 dB. Based on the average insertion loss of the RF MEMS die this results in less than 0.1 dB of insertion loss per transition. The insertion loss per transition results are truely outstanding for

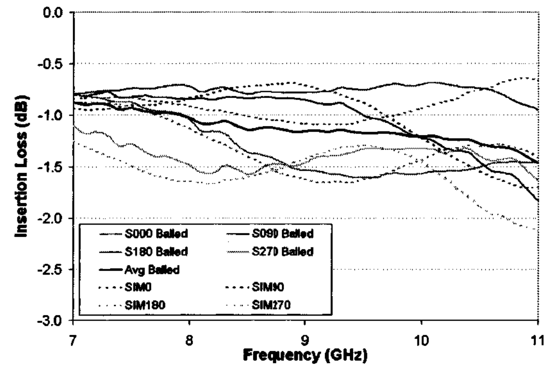

Fig. 5. Measured and modeled response of the packaged RF MEMS phase shifter, average in-band insertion loss of 1.14 dB.

TABLE I
Average Switching Time, in Microseconds, Based on Five Switches

State	Rise Delay	Rise Time	Total Rise	Fall Time
180	21.0	4.3	25.3	57.3
90	12.0	14.6	26.7	65.8
0	7.2	19.3	26.5	88.3
Average	13.4	12.8	26.2	70.4

this band not only for MEMS packaging, but for packaging in general.

As fabricated, the MEMS phase shifter was off in the 270° state by about 37°. This phaser shifter performance was improved in the packaged version by empirically increasing the length of associated grounding straps. This modification resulted in a phase error improvement to less than 3.3° at 9.0 GHz for any phase state.

Although switching times of actual RF MEMS switches have been reported [3], there have been no reports of switching times for actual circuits. The reported measured RF MEMS switch switching times have been in the range of 5 to 10 μs. In Table I are the measurements that were made on the packaged 2-bit phase shifters with average turn-on (delay plus rise) times of 26 µs and average fall time of 70 µs. It is believed that the package has negligible effect on switching times, therefore the reported times are associated with switching multiple MEMS switches. It was observed that as the number of switches that were activated increased, the rise and fall times increased, while the delay time decreased. This resulted in a turn-on time that was roughly independent of the number of switches that were switched. Delay time was defined to be the time the pulse was applied until the phase shift changed by 10%. Rise and fall time was the time required to change from 10% to 90% of the final response. The difference in times between the individual switching times and the circuit switching times could be related to the following different items.

There are at least two possible reasons for the additional turn-on time. One is that not all of the switches activate at the same voltage and the other is that the delay (not previously reported) is comparable to the respective rise and fall times. Since these parts were fabricated, process improvements have been made to significantly reduce the variation in pull-in voltage, which should reduce the rise time. For the turn-off times, the major factors that come into play are the variation in the membrane residual stress and stiction. The impact on overall switch performance by reducing the turn-off time factors are presently being investigated and ways to reduce the turn-off times are being determined.

IV. Conclusion

The success of low loss X-band MEMS packaging has been demonstrated in a thick- film BGA package. The measured performance for the transition was less than 0.1 dB with a resulting packaged 2-bit phase shifter insertion loss of 1.14 dB. It was demonstrated that the performance of the MEMS phase shifter could be improved to less than 3.3° at mid-band, 9.0 GHz. The first reported measurements of switching times of a MEMS circuit were reported.

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