Ka-Band RF MEMS Phase Shifters

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***Abstract*—As the need for low-loss phase shifters increases, so does the interest in radio frequency (RF) MEMS as a solution to provide them. In this paper, progress in building low loss Ka-band phase shifters using RF MEMS capacitive switches is demonstrated. Using a switched transmission line 4-bit resonant phase shifter, an average insertion loss of 2.25 dB was obtained with better than 15-dB return loss. A similar 3-bit phase shifter produced an average insertion loss of 1.7 dB with better than 13-dB return loss. Both devices had a phase error of less than 13° in the fundamental states. To our knowledge, these devices represent the lowest loss Ka-band phase shifters reported to date.**

***Index Terms*—Ka-band, MMIC, phase shifter, RF MEMS.**

I. Introduction

RF MEMS technology is a key innovation for building low-loss phase shifters and other control circuits at millimeter-wave frequencies. Traditional electronic phase shifters are generally built on GaAs and use MESFET's [1] or pHEMT's as switches. These devices switch between different line lengths or switch between different low- and high-pass filters to achieve the desired phase shift. Because of these comparatively lossy switches, the average loss of a Ka-band 4-bit phase shifter that uses the best pHEMT switches is approximately 6.5 dB [2]. Another topology exists that uses distributed MEMS devices to change the phase velocity over a line to produce a phase shift, but the predicted loss of this phase shifter is still 5.1 dB at Ka-band [3]. Decreasing the loss for an array of phase shifters can drastically reduce cost, weight, and heat dissipation problems by requiring fewer amplifiers to drive the phase shifters. RF MEMS technology provides an option of using an extremely low-loss switch in phase shifter designs in order to drastically reduce insertion loss throughout a phase shifter.

RF MEMS capacitive membrane switches have already demonstrated low loss and low parasitics at frequencies through 40 GHz [4]. Utilizing these switches in this Ka-band phase shifter allows us to eliminate a major loss component in traditional phase shifters and thus drastically reduce the overall RF loss through the phase shifter. In addition, by building these devices on silicon, in the future we can integrate the CMOS control circuitry directly on the chip to further reduce complexity and cost. Add in wafer-level packaging and RF MEMS phase shifters become extremely attractive for low-cost, high-performance phased antenna arrays. This paper describes progress made in exploiting these devices in the fabrication of low loss phase shifters in the Ka-band.

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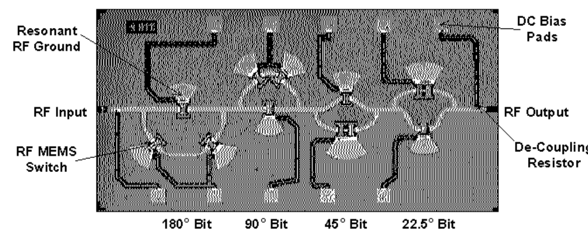

Fig. 1. Photograph and schematic of 4-bit MEMS phase shifter.

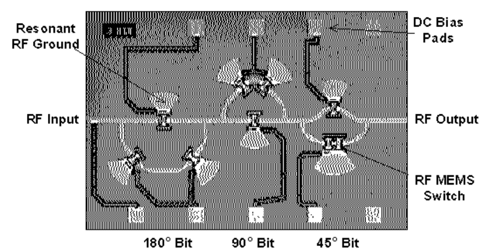

Fig. 2. Photograph and schematic of 3-bit MEMS phase shifter.

II. Design

The Ka-band phase shifter design utilizes one-bit sections of switched delay lines on microstrip and a resistive biasing network. Fig. 1 shows a schematic of the Ka-band 4-bit phase shifter. Fig. 2 shows a similarly developed 3-bit phase shifter. Both designs are built on 6-mil high-resistivity silicon and feature a via-less topology using resonant stubs as virtual RF grounds. By switching in different lengths of transmission line, phase shifts relative to the zero state or "reference" state are obtained. The switching is done using shunt RF MEMS capacitively coupled switches. To turn off a section of line, two quarter-wave transformations occur from the tip of the resonant stub to the tee junction on the RF signal trunk line. The first quarter-wave transformation is from the end of a quarter-wave stub to the center of the RF MEMS switch. The end of the stub is an open so the center of the switch becomes a short at the desired frequency. The second quarter-wave transformation is from the center of the switch to the tee junction. This transformation translates the short at the center of the switch to an open at the tee junction. These lengths are not physically a quarter wavelength because the capacitive effect of the RF MEMS switch. The length of the line was optimized to account for the change in phase velocity. Because the RF signal sees an open at this point, the

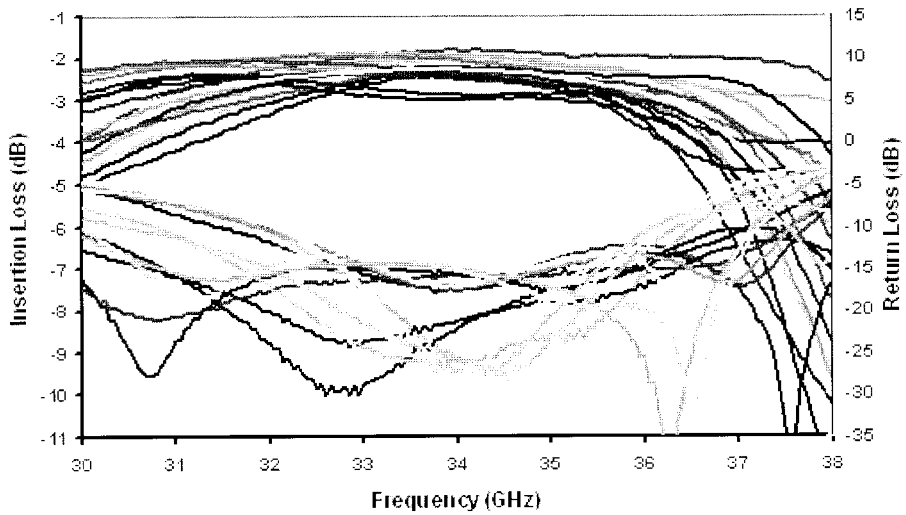

Fig. 3. 4-bit phase shifter performance.

signal travels down the desired path. Because all these quarter-wave transformations depend on there being a 90° phase shift, this is a resonant design. By designing quarter wavelengths for the target frequency, you can easily obtain over 5% of bandwidth.

Each bit in this configuration is designed in the same fashion. There are two paths created. One is the reference path, and the other is made to be a certain length longer corresponding to the desired phase shift. In this case, the first bit has 180° of extra line length in the delay path compared to the reference path. Thus, when the switches are actuated in the reference path, the signal propagates through the delay path and travels 180° further than in the reference path. A similar design procedure is followed in the subsequent bits. The next bit's delay path is 90° longer than the reference, then 45° and then 22.5°. Each bit is then cascaded together. The result is a resonant phase shifter that shifts from 0° to 337.5 ° in 22.5° steps. The three-bit phase shifter is exactly the same as the four bit variety except that the 22.5° bit is omitted.

The resistive biasing network is routed to the switch membrane via the resonant stub. A bias resistor of 10 kΩ is used in each bias path to isolate the dc and RF signals. The resulting RC time constant is much less than the switching time of the MEMS switch so the total switching time is unaffected by the dc bias network. By biasing the membrane with voltage and keeping the line at ground, an electrostatic force is created from the electrode to the membrane. When the voltage applied to the membrane is large enough, the membrane will be pulled down and form a high-value capacitor through a layer of dielectric that connects the signal line and the resonant stub. The RF signal sees this interface as a short and treats it as such. Because there is no dc connection, the voltage across the membrane and electrode remains high and keeps the "holding" force present. This represents an actuated switch. The typical capacitance value for our RF MEMS switch in the actuated state is 3 pF. When the switch is not actuated, the RF signal sees a very small value air-gap capacitor with a value of 33 fF. The ratio of the "on" capacitance to the "off" capacitance (∼100) allows us to direct the RF signal.

TABLE I
4-BIT PHASE DATA AT 35 GHz

Phase State	0.0	22.5	45.0	90.0	180.0
Measured	0.0	10.4	32.0	92.6	172.4
Delta	0.0	-12.1	-13.0	2.6	-7.6

III. RESULTS

The performance of the 4-bit phase shifter is shown in Fig. 3 and Table I. The insertion loss of the phase shifter at 34 GHz varies from 1.8 dB for the shortest state (0°) to 3.0 dB for the longest (337.5°), achieving an average of 2.25 dB. The return loss is better than 15 dB for all states. The fundamental phase states are all within 13°. Switching was achieved by applying a dc voltage of 45 Vs across the membrane and line. The switch actuates in approximately 3–6 μs and releases in about the same amount of time. Line loss at 35 GHz was measured to be 0.7 dB/cm. Based on an average line length of 1 cm including an average of six switches at 0.25 dB/switch, the predicted average loss for this four-bit phase shifter was 2.2 dB.

The performance of the 3-bit phase shifter is shown in Fig. 4 and Table II. The insertion loss of the phase shifter at 34 GHz varies from 1.4 dB for the shortest state (0°) to 2.2 dB for the longest (315°), averaging 1.7 dB. The return loss is better than 13 dB for all states. The fundamental phase states are all within 13°. The average line length of this phase shifter was 0.66 cm with an average of 4.5 switches so the predicted average loss of this three-bit phase shifter was 1.59 dB.

IV. CONCLUSIONS

Both three-bit and four-bit Ka-band phase shifters were constructed using a resonant switched transmission line microstrip topology. RF MEMS capacitive switches were used

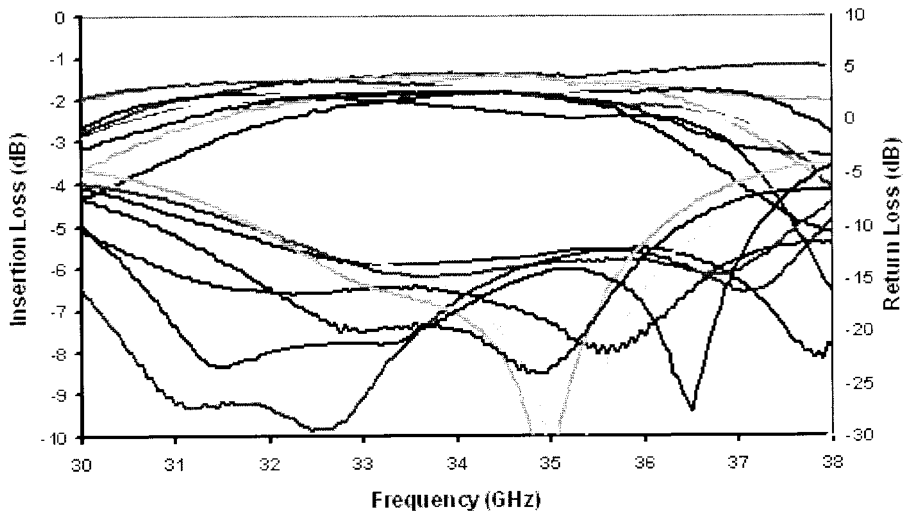

Fig. 4. 3-bit phase shifter performance.

TABLE II
3-BIT PHASE DATA AT 35 GHz

Phase State	0.0	45.0	90.0	180.0
Measured	0.0	31.9	91.2	172.4
Delta	0.0	-13.1	1.2	-7.6

to perform two quarter-wave transformations that allowed us to switch between different delay paths, thus shifting the phase. The result was a 0° to 337.5° phase shifter with 22.5° steps for the four-bit phase shifter and a 0° to 315° phase shifter with 45° steps for the three-bit phase shifter. The average insertion loss was 2.25 dB for the four-bit phase shifter and 1.7 dB for the three-bit phase shifter. Both of these numbers were within 10% of our predicted losses. To the best of our knowledge, these phase shifters represent the lowest insertion loss of any *Ka*-band phase shifter reported to date.

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REFERENCES

[1] M. J. Schindler and M. E. Miller, "A 3 bit K/Ka band MMIC phase shifter," in *Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, 1988, pp. 95–98.
[2] P. Stenger, M. Sarantos, E. Niehenke, H. Fudem, C. Schwerdt, F. Kuss, D. Strack, G. Hall, and J. Masti, "A miniature, MMIC one Watt W-band solid-state transmitter," in *IEEE MTT-S Dig.*, 1997, pp. 431–434, 1997.
[3] N. S. Barker and G. M. Rebeiz, "Optimization of distributed MEMS phase shifters," in *IEEE MTT-S Dig.*, 1999, pp. 299–302, 1999.
[4] C. L. Goldsmith, Z. Yao, S. Eshelman, and D. Denniston, "Performance of low loss RF MEMS capacitive switches," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 269–271, Aug. 1998.