KA-BAND RF MEMS PHASE SHIFTERS FOR PHASED ARRAY APPLICATIONS

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ABSTRACT

RF MEMS switches provide a cheap and effective way to substantially reduce loss in RF and Microwave MMICs. 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 2.25dB was obtained with better than 15dB return loss. A similar 3-bit phase shifter produced an average insertion loss of 1.7dB with better than 13dB return loss. A simple, low loss way to package these devices is also presented.

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 MESFETs [1] or pHEMTs 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 6.5dB [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 5.1dB 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 reduces a major loss component in traditional phase shifters and thus drastically reduce the overall RF loss through the phase shifter. In the future, we can integrate CMOS control circuitry directly on the RF MEMS 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.

PHASE SHIFTER DESIGN

The Ka-band phase shifter design utilizes one-bit sections of switched delay lines on microstrip with a resistive biasing network. Figure 1 shows a schematic of the Ka-band 4-bit phase shifter. The 3-bit phase shifter is exactly like the 4-bit without the smallest bit. Both designs are built

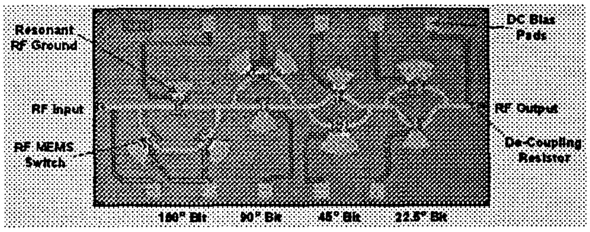

Figure 1 : Photograph of a 4-bit MEMS phase shifter

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on 6mil thick 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 path that is actuated creates a resonant open at the tee junction to direct the RF signal down the correct path. Because all these quarter-wave transformations depend on there being a 90° phase shift, this is a very 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 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 22½°. Each bit is then cascaded together. The result is a resonant phase shifter that shifts from 0° to 337½° in 22½° steps. The three-bit phase shifter is exactly the same as the four bit variety except that the 22½° bit is omitted.

The resistive biasing network is routed to the switch membrane via the resonant stub. A bias resistor of 10kς 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. 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 an RF MEMS switch in the actuated state is 3pF. When the switch is unactuated, the RF signal sees a very small value air-gap capacitor with a value of 33fF. The ratio of the "on" capacitance to the "off" capacitance (~100) allows us to direct the RF signal as needed.

PACKAGING DESIGN

Because of the sensitivity of RF MEMS switches to the environment, all efforts must be made to keep the membranes away from moisture and air turbulence. To be of practical use in a system, a package is needed to shield the devices from these adverse environmental conditions as well as general assembly handling. Traditional MMIC packages place the MMIC in a box and hermetically seal it. The connections are made inside the box that allow the microwave and DC signals to get passed through via traditional microwave and DC feedthrus. Passing a 35GHz signal through one of these traditional connectors is very lossy relative to the loss of this phase shifter. All the benefits gained from using a low loss phase shifter in a system are lost. A quick and easy package for these devices involves etching a small cavity (~7mils) in a lid material (glass) and using nonconductive epoxy to adhere the edge of the cavity to the MMIC. Glass is used as the lid material because of it's low dielectric constant, optical transparency and close CTE match to silicon. The low dielectric constant of glass minimizes the perturbation of the lid on the circuit while the optical clarity allows us to visually see the RF MEMS switch actuating. The total size of the lid is just slightly smaller than the MMIC die allowing I/O lines to be exposed and bonded to. The etched glass lid provides a shelter for the RF MEMS switches without having to use expensive and lossy connectors.

PHASE SHIFTER RESULTS

The performance of the 4-bit phase shifter is shown in Figure 2 and Table 1. The insertion loss of the phase shifter at 34GHz varies from 1.8dB for the shortest state (0°) to 3.0dB for the longest (337½°), achieving an average of 2.25dB. The return loss is better than 15dB for all states. The fundamental phase states are all within 13°. Switching was achieved by applying a DC voltage of 45 volts across the membrane and line. The switch actuates in approximately 3-6µs and releases in about the same amount of time. Line loss at 34GHz was measured to be 0.7dB/cm. Based on an average line length of 1 cm including an average of six switches at 0.25dB/switch, the predicted average loss for this four-bit phase shifter was 2.2dB.

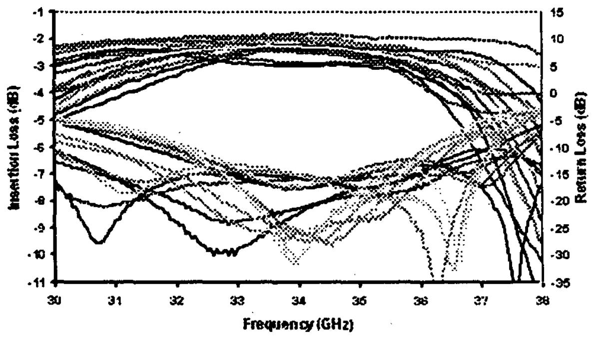

Figure 2 : 4-bit phase shifter performance

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

Table 1 : Phase of the four fundamental states of the 4-bit phase shifter

The performance of the 3-bit phase shifter is shown in Fig. 3 and Table 2. The insertion loss of the phase shifter at 34GHz varies from 1.4dB for the shortest state (0°) to 2.2dB for the longest (315°), averaging 1.7dB. The return loss is better than 13dB for all states. The fundamental phase states are all within 13°. The average line length of this phase shifter was 0.66cm with an average of 4.5 switches so the predicted average loss of this three-bit phase shifter was 1.59dB.

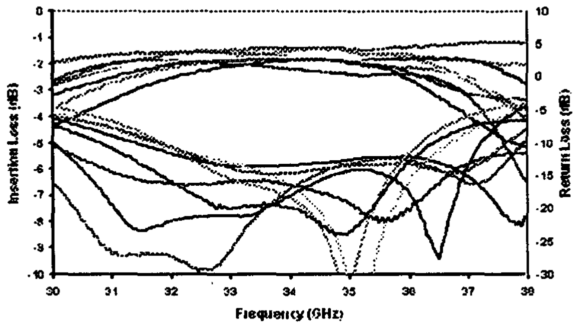

Figure 3 : 3-bit phase shifter performance

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

Table 2 : Phase of the three fundamental states of the 3-bit phase shifter

PACKAGING RESULTS

Packaging these phase shifters introduces two additional sources of loss to the devices. Additional line length is the first source of loss. We needed to add roughly 0.2cm of line length to each side to allow room for the lid seal area, alignment tolerances and access to the I/O lines with an auto-bonder. This corresponds to an additional loss of 0.3dB to 0.35dB per phase shifter depending on the line loss. The second source of packaging loss is the actual transition beneath the glass seal area. By placing a piece of glass directly on the microstrip line using a 1-2mil thick layer of epoxy to adhere it, an additional dielectric loss occurs. This loss was measured to be about 0.2dB per transition for a total transition loss of 0.4dB per phase shifter. These two numbers together yield a total packaging loss of 0.7dB to 0.75dB per phase shifter. A picture of the dual-channel lidded 3-bit phase shifter is shown in Figure 4.

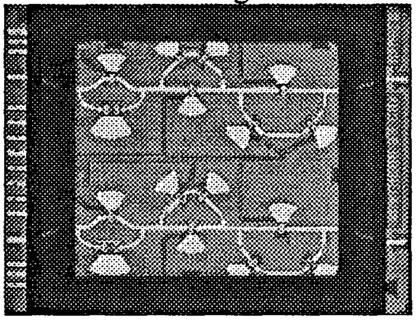

Figure 4 : Picture of lidded 3-bit phase shifter

The impedance and phase velocity changes due to the presence of the 7mil glass cavity over the device is very minimal. The impedance of the line changes very slightly so that an insertion loss change is not noticeable. The only effect that is seen is that the resonant frequency of the phase shifter is shifted down by 0.4GHz.

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 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 337½ ° phase shifter with 22½° 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 2.25dB for the four-bit phase shifter and 1.7dB 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.

Packaging these devices is a critical step in getting them introduced into systems. We have taken a first look at what a low loss package looks like and discussed the results. We saw that by packaging the phase shifter we introduced 0.7dB to 0.75dB additional loss into the system at Ka-band. We also saw a downward shift of 0.4GHz for a 7mil etched cavity. Using this information we can design a phase shifter 0.4GHz higher than our target frequency, knowing that with the lid in place the response will shift downward by that same amount. This low loss, low impact packaging aspect is essential in fully utilizing the potential of these phase shifters.

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