**Abstract**— This paper presents for the first time a four-bit MEMS phase shifter fabricated on an organic, flexible, low permittivity material. A microstrip switched-line phase shifter has been optimized at 14 GHz for small size and excellent performance. In addition, the MEMS phase shifter was packaged in an all-organic, flexible, low permittivity, Liquid Crystal Polymer (LCP) package. The improved geometry of the reduced size phase shifter is 2.8 times smaller than a traditional switched-line phase shifter and is much less lossy. For the four-bit phase shifter, the worst case return loss is greater than 19.7 dB and the average insertion loss is less than 0.96 dB (0.24 dB/bit or 280°/dB). The average phase error is only 3.96°. It has been demonstrated that the addition of the LCP package has a negligible effect on the phase shifter performance, but will enable the device to remain flexible and protected against various environmental conditions.

I. INTRODUCTION

To date, four-bit phase shifters have been documented in various system-on-chip (SOC) devices. They have been published on various materials, including silicon [1] and GaAs [2]. Various switching elements have been used including FETs [2], PIN diodes [3], and in recent years MEMS [1]. Currently published four-bit phase shifter papers have several shortcomings. First, they are all fabricated on non-organic substrates. Some of these substrates are costly, such as GaAs. Second, many of them use solid-state switching elements. PIN diodes, FETs, and other solid state switches are typically lossier, consume more power, and have more distortion at high frequencies than MEMS switches. Third, none of the published four-bit phase shifters are packaged. This paper presents a solution to all of these issues.

There is an increased interest in moving towards system-on-package (SOP) RF Front End technologies. SOP offers design simplicity, lower cost, higher system function integration, better electrical performance, and various 3D packaging capabilities [4]. This paper presents for the first time an SOP RF Front End four-bit MEMS phase shifter on an organic substrate. This paper furthers the all-organic, flexible packaging technology by housing more than one MEMS devices in a single package and presents for the first time a packaged phase shifter on an organic, flexible, and low permittivity substrate. The organic substrate serves as both the RF substrate and the packaging material (superstrate).

RF MEMS have previously been integrated monolithically on Printed Circuit Board (PCB) substrates. In [5], the authors integrated RF MEMS switches with a diversity antenna on FR4 substrate. FR4 is an organic, low permittivity substrate like LCP but it does not have the same flexibility and low-loss at high frequency characteristics like LCP. Wafer-scale packaging is discussed in [5] but it has been realized in this paper.

Phase shifters are an integral part of RF systems. Microwave devices on non-semiconductor substrates (i.e. Liquid Crystal Polymer, LCP) have been explored due to their low-cost, low-loss, flexibility, and near-hermetic nature [6]. The first MEMS phase shifter on a flexible, organic substrate was presented at the 35th European Microwave Conference [7]. One-bit and two-bit phase shifters were presented. However, those phase shifters were not miniturized nor were they packaged. This paper continues the work presented in [7] by greatly shrinking the size, lowering the loss, expanding to four bits, and integrating into an all-organic package.

II. GENERAL PHASE SHIFTER DESIGN AND PACKAGING TECHNOLOGY

As will be discussed in this paper, integrating RF devices in an all-LCP package does not require any additional design considerations on the devices themselves. That is, the design of the MEMS phase shifter can be done completely independent of the packaging layout. Therefore, each of these topics are explained separately.

A. General Phase Shifter Design

The LCP material used has a thickness of 25 µm or 100 µm, a permittivity (εr) of 3.1, and a tan δ of 0.004 [6]. To demonstrate that a MEMS phase shifter can be enclosed in an all organic, flexible package, a four-bit switched-line microstrip phase shifter was designed at 14 GHz for phase shifts between 0° and 337.5° in 22.5° increments (16 cases). Traditional microstrip theory was used to design the phase shifter. A layout of the final four-bit phase shifter is shown in Figure 1.

The phase shift is related to the change in length between the reference and the phased path. This is described mathematically by Equation 1 where ΔΦ is the phase difference (deg), λ is the wavelength, and l is the line length [8].

\[
ΔΦ = \frac{360}{λ}(l_{\text{phased path}} - l_{\text{reference path}}) \quad (1)
\]
In order to apply the necessary bias voltage to actuate the MEMS switches, bias pads were designed and placed on each of the signal paths (not shown in Figure 1). When a DC voltage is applied to the bias pad, electrostatic force pulls the switches (which are DC grounded) towards the signal line. A layer of silicon nitride deposited over the signal line prevents switch metal to signal line metal contact. Therefore, no DC current can flow but the capacitance between the switch and the signal line is large enough for RF energy to pass through. The down state capacitance of the MEMS switch is approximately 2.5-4 pF and the up state capacitance is approximately 90 fF. A fabricated four-bit phase shifter with bias pads is shown in Figure 2.

**B. General Packaging Technology**

The phase shifter signal lines and MEMS switches were fabricated on the LCP substrate. In addition, a piece of 25 µm thick LCP bond ply layer was placed on top of the fabricated substrate. This layer is electrically the same as the thicker 100 µm material but it melts at a slightly lower temperature. To prevent the MEMS switches from being damaged by the second LCP layer, three cavities were laser-micromachined to expose each of four tree-junctions, which contain four MEMS switches each. The middle two tree-junctions share a cavity due to their close proximity.

All of the windows and cavities were micromachined using a CO₂ laser. These holes align with the switches on the substrate layer to create a cavity large enough and deep enough to prevent contact between the switches and the cavity walls. On top of these two layers of LCP, a third layer of 100 µm thick LCP is stacked to complete the package. In order to access the metal signal lines from outside the package with DC or RF probes, windows over the bias pads were laser etched in the middle and top layers to allow direct contact. The DC bias pads were connected to a voltage source through a high impedance DC probe. Since the DC probe is of a much higher impedance than the signal lines, very little RF power is leaked into the DC probe. Alternatively, high impedance films could be deposited on the LCP substrate and used with a standard Tungsten DC bias tip to achieve the same effect. This would be the biasing approach taken for a fielded device where all the bias lines are connected. The placement of the windows and cavities is demonstrated in Figure 2. A side view of the laser drilled cavities and packaged MEMS switches is shown in Figure 3.

By using an all-LCP package, the protected device(s) will benefit from the low-loss and near-hermetic nature of the packaging material. Additionally, this packaging technique is ideal for applications that require flexible circuits. The superstrate can be permanently bonded to the substrate using thermocompression, ultrasonic, or laser bonding [9]. A top view of an LCP sample that has been packaged using thermocompressive bonding is shown in Figure 4.

It has been demonstrated that single RF MEMS switches can be packaged using this technique [9]. Since the permittivity of LCP is approximately 3.1, which is close to the permittivity of air \((\varepsilon_r = 1)\), the presence of the superstrate has a minimal effect on the overall device performance. That is, the dielectric discontinuity between LCP and air is much smaller than the discontinuity between a high permittivity material (silicon, for example) and air. It has been shown in [9] that the LCP-air discontinuity is small enough that an LCP superstrate layer can be added with a minimal effect on the device performance.
III. REDUCED-SIZE METHODOLOGY

Switched-line phase shifters are widely used because they are straightforward to design, fabricate, and integrate with other microwave devices. Unfortunately, the overall size of the switched-line geometry is comparable to the wavelength for each bit. Since multibit phase shifters are usually desired, this can result in a phase shifter that is much larger than the other microwave components in an RF system. For this reason, a number of changes were made to the traditional layout presented in [7] to decrease the size. These design changes are detailed below. By incorporating these layout changes, the overall area was reduced by a factor of 2.8. The length was reduced by a factor of four. In addition to the size reduction, the line length and number of MEMS switches traversed compared to a traditional implementation were each reduced by a factor of two. This results in half the line loss and half the switch loss by using this implementation. A size comparison of the modified layout compared to a traditional layout is shown in Figure 5.

A. Series-Shunt Modification

Instead of cascading four one-bit phase shifters in series (as demonstrated in Figure 5), four shunt phased paths were cascaded with another four shunt phased paths (hence the series-shunt distinction). This was demonstrated in Figure 1. In order to generate all sixteen possible cases, a \(0^\circ\) reference path must occur in every series portion of the phase shifter. In addition, the \(0^\circ\), \(90^\circ\), \(180^\circ\), and \(270^\circ\) phased paths must be in one section and the \(0^\circ\), \(22.5^\circ\), \(45^\circ\), and \(67.5^\circ\) phased paths must be in another section to create all 16 cases. In order to make this feasible for really short phased paths (like the \(22.5^\circ\) case) and really long phased paths (like the \(270^\circ\) case), the shortest phased paths were elongated by a wavelength. This is why the smallest phase shifts have longer line lengths than the largest phase shifts.

This series-shunt technique was previously published by the University of Michigan and Rockwell Scientific using Single Pole Four Throw (SP4T) MEMS switches [1], [10]. The switches used in this paper are SP4T as well, but they are implemented differently than in [1]. For example, we chose not to use via holes which add an unnecessary level of complexity to the design and fabrication. The switches presented in this paper offer the same loss performance without the use of vias.

Previous works that claim “small”, “reduced”, or “minia-ture” size multibit phase shifters always use high dielectric materials, such as silicon or GaAs, that have permittivities between 11 and 13 [11]. This is because the wavelength of a microstrip line is inversely related to the square root of the permittivity. Microstrip phase shifters on high dielectric materials will always be much smaller than those on low dielectric materials. The cost of prototyping devices on LCP is similar or less than that of silicon or GaAs. However, since the material cost is much lower there are cost benefits to using LCP on a large scale [9].

B. High Impedance Modification

Instead of using the standard 50\(\Omega\) input impedance, 100\(\Omega\) was used. By making this change, the line width decreased from 240 \(\mu\)m to 65 \(\mu\)m. This allowed for more signal lines to be placed in less area. In practice, high impedance patch antenna arrays which would utilize this type of phase shifter are not uncommon [12]. However, a 50\(\Omega\) to 100\(\Omega\) transition could be added for integration with other standard microwave components.

C. Curled Signal Line Modification

Instead of using the traditional rectangular phased paths, the lines were curled inward to minimize the overall area (as shown in Figures 1 and 5). Since multibit phase shifters are often used to steer antenna arrays it is necessary to keep the overall size as small as possible. Careful attention was given to minimize coupling between the signal lines. A full wave HP-ADS Momentum (method of moments) simulation was performed to determine the amount of coupling that would result between two 65 \(\mu\)m wide, 2.5 mm long signal lines at 14 GHz. These results are shown in Figure 6.

Most of the distancing between signal lines used in the layout is 300-400 \(\mu\)m, which corresponds to 5.8-3.6\% transmitted power. However, in some areas, distances as small as 150 \(\mu\)m were necessary. The lines in these areas were placed at oblique angles to each other to minimize the coupling.
Fig. 6. Percentage of Power Transmitted Between Coupled Signal Lines for a Given Spacing at 14 GHz

Fig. 7. Demonstration of Iterative Approach for Impedance Matching

D. Impedance Matching

Since curved microstrip lines are being used to reduce the size, impedance matching must be done to compensate for the additional parasitic impedance. Instead of using additional matching devices, such as stubs [1], all impedance matching was handled through the signal lines themselves. Lines that require a higher impedance match were made thinner and lines that require a lower impedance match were made wider. This was performed in a full-wave simulator using an iterative method as demonstrated in Figure 7.

Since the arcs are the shortest part of the signal line, they were used to do the impedance matching. The center case in Figure 7 uses a curved line with the device characteristic impedance (100Ω). The leftmost case has a slightly higher impedance and the rightmost case has a slightly lower impedance. The impedance was varied until the lowest insertion loss was achieved. The overall size of the circuit does not change by using this method of impedance matching. The optimized impedance values for a section of the phase shifter are shown in Figure 8.

IV. TREE-JUNCTION DESIGN

To simplify the design and fabrication process, all of the MEMS switches are SP4T. Since one signal must be split among four different phased paths, a four-way Y-junction (or tree-junction) was designed. The geometry of the tree-junction used is shown in Figure 9.

Each of the four output stubs are the same width as those of the other signal lines and are \( \lambda/65 \) long at the design frequency (or 220 \( \mu \)m). This is sufficiently small to prevent RF energy from entering the stubs that are associated with non-activated MEMS switches (that is, in the up state). Using longer lines increases the amount of leakage power into these stubs. Using shorter stubs forces the layout to be too dense. The \( \lambda/65 \) length is optimal for this particular layout. However, a good rule of thumb is to use line lengths less than \( \lambda/25 \) to avoid excessive leakage power. Fine tuning can be done using a full-wave simulator.

Each stub is placed at 30° or 60° off the main axis. These values can vary, but symmetry across the main axis is necessary for symmetric distribution of power. Very wide angles can be used with very short stubs to prevent layout crowding (as in this case). Alternatively, very narrow angles can be used with long stubs to keep the layout small. To demonstrate that the angle can vary without greatly effecting the performance, a full wave simulation was run with one stub that varies the bend angle from 0° to 90°. The results are shown in Figure 10.

For all angles between 0° to 90°, the effect of the bend is negligible. The additional phase increase from the bend discontinuity is 0.39° and 0.66° for the 30° and 60° bends, respectively. The additional insertion loss is too small to measure. An example of a fabricated tree-junction with MEMS switches on LCP was shown in the cutout of Figure 2.
V. SIMULATION RESULTS

A full-wave simulation was performed using HP-ADS Momentum for the 4-bit phase shifter. The design was optimized for low-loss and a phase error less than three degrees. $S_{11}$ and $S_{21}$ simulation results for four of the sixteen possible phase shifts is shown in Figure 11.

As expected, the phased paths with the longest lengths have more loss than the shorter phased paths. The 67.5 degree configuration has the longest phased path and the 90 degree configuration has the shortest phased path in the system. The MEMS switch and metal losses were not modeled in these simulations. Therefore, it is expected that the insertion losses shown in Figure 11 will be much less than the measured results.

VI. MEMS FABRICATION ON LCP

Fabricating on a flexible, organic substrate is not as straightforward as using a smooth, flat substrate like silicon. Being a flexible material, it is prone to curling. This effect becomes more pronounced throughout processing due to the fluctuation of temperature from the various baking, deposition, and etching steps. The Coefficient of Thermal Expansion (CTE) of LCP is 17 ppm/$^\circ$C in the horizontal (x,y) directions and 24 ppm/$^\circ$C in the vertical (z) direction [13]. However, the CTE of LCP can be engineered to any value between 3 and 30 ppm/$^\circ$C [6].

Since optical lithography with a 3-5 µm resolution cannot be performed on a curled substrate, it is necessary to mount the sample to a flat, cleanroom grade material before processing. Temporary mounting can be done using a spin-on or roll-on adhesive. Permanent mounting can be done using a thermal bonding technique. Since the substrate is also an organic polymer, surface roughness is an issue. The surface roughness is usually on the order of 2-5 µm. Given that the MEMS switch is generally suspended 2-3 µm above the substrate, the surface roughness can be large enough to prevent the switch from deflecting. To solve this problem, each sample is mechanically polished using an alumina slurry. After polishing, the sample will have a surface roughness between 10-50 nm, which is smooth enough for MEMS switch operation [7].

After polishing and mounting to a flat material, the following procedure, demonstrated in Figure 12, was used in fabricating the MEMS phase shifters. Gold transmission lines were electron beam evaporated and patterned using hard contact optical lithography. A silicon nitride ($\text{Si}_3\text{N}_4$) layer was deposited using low-temperature Plasma Enhanced Chemical Vapor Deposition (PECVD). The silicon nitride was then patterned and etched using a Reactive Ion Etch (RIE) process everywhere except for the MEMS switch contact areas. Photoresist was patterned to provide a sacrificial layer for the switches. Gold for the switch membrane was evaporated, patterned, electroplated to 2 µm, and etched. The sacrificial layer was stripped away leaving the MEMS switches suspended above the signal lines. The sample was dried using carbon dioxide ($\text{CO}_2$) at the supercritical point to prevent switch
collapse due to water surface tension. A picture of a fabricated MEMS phase shifter is shown in Figure 2.

VII. THERMOCOMPRESSION BONDING OF LCP

LCP is ideal for thermocompression bonding because it can be manufactured to melt at either 315°C (high melt LCP) or 290°C (low melt LCP) [6]. For this packaging method, the low melt LCP is used as the 25 µm thick bond ply and the high melt LCP is used as the substrate and superstrate layers. When the substrate (with MEMS phase shifters), bond ply, and superstrate layers are sandwiched together and placed inside a thermocompression bonding machine at a temperature between 290°C and 315°C, the low melt LCP bond ply will melt and adhere uniformly to the outer core layers. This creates the all-organic, near-hermetic package [9]. Other materials require high voltages or metal rings to adhere the packaging layer. A thermocompression bonding machine is ideal for uniform bonding and maximum control of the recipe, but this process could be performed using two hot plates or an oven.

VIII. CALIBRATION AND MEASUREMENT

Measurement results were taken using high impedance DC probes to apply the switch bias voltage. Thru-Reflect-Line (TRL) calibration was performed on wafer to remove the connector and cable losses. Calibration was done without the superstrate layer so the effect of the packaging can be measured. The difference in the input impedance with and without the superstrate is only 4Ω, which should not have a substantial effect on the response [9].

At 14 GHz the line loss is approximately 0.37 dB/cm for both unpackaged and packaged configurations. The average variation in the line loss between the unpackaged and packaged measurements is 0.00625 dB between 8 GHz and 20 GHz. The maximum variation is 0.0239 dB. Clearly, the 4Ω input impedance difference has a negligible effect on the response.

IX. RESULTS

The loss measurement results for the four-bit MEMS phase shifter without the top superstrate layer (unpackaged) are shown in Figure 13. The worst case S11 is -20.8 dB and the average S21 is -0.95 dB. This is a per-bit loss of only 0.238 dB. The loss measurement results with the top superstrate layer (packaged) are shown in Figure 14. The worst case S11 is -19.7 dB and the average S21 is -0.96 dB. This is a per-bit loss of only 0.240 dB. Both cases have approximately 280°/dB loss.

The phase error measurement results without the top superstrate layer (unpackaged) are shown in Figure 15. The average phase error is 3.96 degrees. The phase error measurement results with the top superstrate layer (packaged) are shown in Figure 16. The average phase error is 6.57 degrees.

In order for this to be a suitable packaging technique, there should be minimal variation in the loss and phase response with and without the superstrate layer. Fortunately, this variation is minor, as shown in Figures 13, 14, 15, and 16. The average S21 loss variation is only 0.013 dB, which is

![Fig. 13. Measured Loss of Unpackaged Phase Shifter. The order of the lines is listed from most lossy to least lossy at 14 GHz](image)

![Fig. 14. Measured Loss of Packaged Phase Shifter. The order of the lines is listed from most lossy to least lossy at 14 GHz](image)

![Fig. 15. Measured Phase Error of Unpackaged Phase Shifter. The order of the lines is listed from most positive to most negative at 14 GHz](image)
practically negligible. The variation in the phase is shown in Figure 17. The average variation is only 3.16 degrees.

To demonstrate the mechanical strength of the package, a 15 pound per square inch (psi) force was applied to the top of the package. This test is necessary to show that the package can withstand the pressure necessary for thermocompression bonding and once bonded can withstand being compressed. A loss and phase comparison of the phase shifter without the package, with the package, and with the package after being subjected to the weight is shown in Figure 18. For brevity, only the shortest (0°) and longest (337.5°) phased paths are shown.

The addition of the weight creates compressive stresses in the LCP around the cavity discontinuities. These stresses extend to the signal line metal which causes small deflections in the MEMS switches. Any changes in the MEMS switch geometry will change the switch capacitance which accounts for the very small variation on the loss and phase. Increasing the size or rounding the shape of the cavities would decrease the compressive stresses in the LCP. This would decrease the effect of the weight or would allow for more weight to be applied.

As expected, adding the superstrate layer to package the

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Fig. 16. Measured Phase Error of Packaged Phase Shifter. The order of the lines is listed from most positive to most negative at 14 GHz

Fig. 17. Difference Between Unpackaged and Packaged S21 Phase. The order of the lines is listed from most positive to most negative at 14 GHz

Fig. 18. Comparison of the Phase Shifter Without a Package, With a Package, and With a Package After Applying 15 psi of Force for the 0° and 337.5° Cases
phase shifter had a minimal effect on the performance. The best case, worst case, and average results are summarized in Table I. In addition to having loss and phase error measurement data comparable to the other published four-bit phase shifter papers, our phase shifters are demonstrated with and without packaging.

These measurement results agree very well with the simulated results. This is expected since a small meshing was used in simulation and fabrication tolerances are usually within 3 \( \mu m \). Simulations calculated that the S11 response would vary from -20 dB to -40 dB at 14 GHz for all sixteen cases. As shown from the data in Table I, there is excellent agreement with the measured values. Furthermore, the simulations correctly predicted the ordering of the insertion loss from least lossy to most lossy. Since the simulations did not include metal and MEMS switch losses, it was expected that the simulated insertion loss would be less than the measured insertion loss.

**X. Conclusion**

For the first time, RF MEMS phase shifter have been packaged on a flexible, organic substrate; specifically, Liquid Crystal Polymer. In addition, this is the first time that a small size four-bit phase shifter was published on an organic material. Several modifications were made to the traditional microstrip switched-line phase shifter layout to reduce the size and improve the performance. Measurement results exemplify the low-loss nature of this polymer at high frequencies. With a worst case return loss greater than 19.7 dB and an average insertion loss lower than 0.96 dB (0.24 dB/bit or 280°/dB), this is the first flexible, organic, packaged, miniature phase shifter with minimal loss.

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