W-Band True-Time Delay Phase Shifters Using Paraffin Microactuators

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Abstract—We report a distributed loaded line phase shifter based on a new class of electro-thermally actuated RF MEMS devices using paraffin phase-change material (PCM). Paraffin is a low loss (tan δ = 6.6×10−4) mechanical phase-change material that exhibits a 15% volumetric change through its solid-liquid transition. Due to its unique electrical and mechanical properties, paraffin PCM variable capacitors exhibit a very low loss which is critical in designing reconfigurable structures. Here, a low-loss paraffin PCM based true-time delay, continuously-tunable phase shifter is designed and optimized. A figure-of-merit of 71.8°/dB is achieved while maintaining a return loss more than 12 dB. Designed phase shifter has a maximum insertion loss of 5 dB for a 360° phase shift. Electro-thermo-mechanical performance of the paraffin PCM device is studied by carrying out a fully coupled multiphysics simulation. Maximum displacement of 0.8 µm is achieved with a 2.6 µm-thick paraffin film. A new fabrication method for the deposition of the thin paraffin film is developed and a fabrication process for the device is presented.

Index Terms—DMTL, paraffin, phase-change material, phase shifter, MEMS, millimeter wave.

I. INTRODUCTION

In the recent years there is an increasing demand for low loss phase shifters at mmW band. Low loss phase shifters are critical components in realizing passive and hybrid arrays. True-time delay (TTD) RF MEMS phase shifters are capable of handling high power and offer high phase shift resolution which results in the high scanning accuracy and high detection range. In addition, use of TTD components, due to the linear dependence of phase shift to the frequency, eliminates the frequency scanning in ultra wide band radars. mmW arrays have application in defense and automotive anti-collision radars (77 GHz) [1], high resolution imaging for detection of small debris and unmanned aerial systems in airport runways (94 GHz) [2].

There are two main approaches in designing TTD phase shifters: switched line and distributed loaded line [3]. Switched line phase shifters offer a higher shift per dB of insertion loss compared to the distributed loaded line at the expense of a discrete limited phase resolution. State-of-the-art RF MEMS based switched line phase shifters are reported to have a figure of merit of 122°/dB at Ku-band [4] and 104°/dB at V-band [5]. Phase resolution of the switched line phase shifters are limited by the number of switches and the their performance depends on the low-loss high isolation switches. On the other hand, analog phase shifters based on distributed loaded line can provide a continuously tunable phase shift. Furthermore, use of an analog bias voltage eliminates the phase quantization error and increases the beam steering accuracy.

Distributed loaded line phase shifter are designed based on periodically loading a high impedance line with variable capacitors. Distributed microelectromechanical transmission line (DMTL) approach was first introduced by Barker et al. and 70°/dB at 75–110 GHz was reported [6], [7]. Analog phase shifters were also implemented using liquid crystals where the phase shift was obtained by tuning the permittivity of the dielectric layer underneath the fixed MEMS bridge and a 42°/dB was achieved at W-band [8]. DMTL can also be implemented digitally and figure-of-merit of 100°/dB was obtained [9]. Drawback of the digital implementation is the decrease in the phase resolution. Furthermore, a complex routing scheme with a parallel bus is required for biasing, whereas analog phase shifters are biased through single line.

In this work we present a DMTL phase shifter using a new class of electro-thermo-mechanical actuators based on paraffin phase-change materials. Paraffin is a low loss dielectric with a loss tangent of 4.5×10−4−6.6×10−4 at 75–110 GHz and dielectric constant of 2.26 [10]. Moreover, paraffin is a mechanical phase-change material (PCM) that undergoes a 15% reversible volumetric change through its solid-liquid transition (75°C). The proposed PCM device exploits the large volumetric change of the paraffin through a thermo-electrical actuation to obtain a variable capacitor. Paraffin-based variable capacitors were first introduced in [11] and [12] where they were integrated with a slot antenna to obtain frequency reconfiguration. Here, a TTD phase shifter is designed by periodically loading a high impedance coplanar waveguide (CPW) transmission line with paraffin PCM capacitors. Electrical phase change is controlled continuously through electro-thermo-mechanical actuation. The designed phase shifter, due to low tangent loss of paraffin, has a low loss which results in a large phase shift per dB of loss. In addition, thermo-electrical-actuation of the device offers a lower actuation voltage (< 5 V) compared to the classical MEMS devices and offers a high resolution tunability.

II. DESIGN

Figure 1(a) shows the top view of the DMTL, where a high impedance (>50 Ω) CPW is periodically loaded with paraffin PCM bridges. CPW line has a center conductor width
of $W$ and a gap of $G$. MEMS bridges have a width of $w$ and the length of $l = W + 2G$ and the periodic spacing between bridges is denoted as $s$. Lumped element model of the unit cell is illustrated in Fig. 1(b) where $L_t$ and $C_t$ are the inductance per length and capacitance per length of the unloaded line, respectively. Paraffin PCM bridge is modeled as a shunt capacitor $C_{\text{var}}$.

In order to maximize the phase shift with the minimum amount of insertion loss, we used the lumped element model and applied the optimization method described in [7] and [13] to maximize phase shift per unit of insertion loss. A 200 µm-thick quartz ($\varepsilon_r = 3.78$) substrate is chosen due to its low loss tangent ($4 \times 10^{-4}$) at mmW band. Total width of the CPW, i.e. $W + 2G$, is fixed to $\lambda_g/8$ at the maximum operating frequency of 110 GHz. In order to maintain a return loss of better than 10 dB, Bragg frequency is chosen to be 250 GHz. Since the volumetric expansion of the paraffin is 15%, capacitance ratio of the paraffin PCM capacitor is fixed as 1.15. For the impedance matching, characteristic impedance ($Z_0$) and attenuation constant ($\alpha_0$) of the unloaded line are extracted. Attenuation constant of the loaded line can be calculated as, $\alpha_t = \alpha_0 \frac{Z_{ld}}{Z_0}$ where $Z_{ld}$ is the impedance of the loaded line at down state and is chosen to account for the highest attenuation. For each $W$ value and fixed capacitance ratio of 1.15, phase shift for each unit cell is calculated. In order to determine the optimum value for $W$, $\Delta \phi/\alpha_t$ is plotted with respect to $W$ as shown in Fig 2. The optimum value for $W$ is found to be 70 µm and corresponding spacing and capacitance values are 102 µm and 21.9 fF, respectively.

III. FULL-WAVE AND CIRCUIT SIMULATION

To verify the design and determine the width of the paraffin PCM capacitors, full-wave simulation of DMTL phase shifter is carried out in Ansoft HFSS. For the simulation, 21 MEMS bridges with a width of 29 µm and initial paraffin thickness of 2.6 µm is considered. Thickness of the paraffin layer is increased to 3.1 µm according to the volumetric expansion of the film. CPW line and the MEMS bridge consists of 0.7 µm-thick gold layer. Value of the variable capacitance and loss resistance is determined by fitting the FEM simulation results to a circuit model using Advanced Design System (ADS) circuit simulator. Fig. 3 shows the return loss and insertion loss of the HFSS full-wave and ADS circuit model and a close agreement between the two models is achieved. Capacitance of the paraffin PCM bridge is found to be 21.98 fF and 25.27 fF in actuated and unactuated states, respectively. The series resistance of the capacitor is found to be 0.28 Ω.

Since the lumped element model of the paraffin PCM capacitor is extracted, circuit simulator is used for the full scale 360° phase shifter. In order to achieve a 360° of phase shift with the capacitance ratio of 1.15, 140 paraffin PCM capacitors are required. Simulated insertion loss and differential phase shift of the full scale phase shifter are shown in Fig. 4. Return loss is better than 10 dB and the 71.8°/dB loss is achieved at 100 GHz. Maximum insertion loss is -5.03 dB for a phase shift
of 360° at 100 GHz and maximum insertion loss difference between various states is 0.5 dB.

IV. MULTIPHYSICS SIMULATION

To evaluate the actuation performance of paraffin PCM device, multiphysics simulation is carried out in COMSOL by coupling the electrical energy, heat convection, conduction, laminar flow, and mechanical motion. Paraffin is modeled as a liquid with temperature dependent density, viscosity, heat capacity and heat conductivity. 3D schematic of the actuator with three MEMS bridges are shown in Fig. 5. The heat source is a Joule heater which consists of a 250 nm-thick and 10 µm-wide meandered line and excited with a DC voltage of 5V. The heat distribution on the heater for the input voltage of 5 V is shown in Fig. 5. The maximum temperature of 89°C (362 K) is reached which is above the phase transition temperature of paraffin (75°C). Von Mises stress is also depicted in Fig. 5. The maximum stress on the MEMS bridge is 16.2 MPa which is well below the yield strength of 0.7 µm-thick gold. Fig. 6(a) shows the transient response of the center displacement of the MEMS bridge where a maximum deflection of 0.8 µm is achieved.

V. FABRICATION

Phase shifters are fabricated using a 6-mask photolithographic process on a 200 µm-thick quartz substrate. First, Joule heaters are fabricated by patterning a 250 nm of gold followed by 1 µm-thick chemical vapor deposition of SiO₂ as the insulating layer. Micrographs of the fabricated heater are shown in Fig. 7. Next, CPW lines are fabricated by deposition a Cr/Au (50/7000 Å) layer. For the deposition of paraffin, a fabrication process based on spin coating is developed.

VI. CONCLUSION

We presented a W-band true-time delay phase shifter based on a new class of electro-thermally actuated RF MEMS devices using paraffin phase-change materials. Paraffin PCM variable capacitors exhibits a very low loss which is critical in designing reconfigurable structures. Here we reported a paraffin PCM DMTL phase shifter with a figure-of-merit of 71.8°/dB while maintaining a return loss more than 12 dB. For
a 360° phase shift, insertion loss of 5 dB is obtained. Paraffin PCM capacitors are shown to have a capacitance ratio of 1.14 with a very low resistance of 0.28 Ω. A fully coupled multi-physics simulation of the electro-thermo-mechanical actuation is carried out in COMSOL. It is shown that for a 2.6 μm-thick actuation layer, 0.8 μm displacement can be achieved. The actuation time for the device is found to be 17.2 ms. A fabrication process for the phase shifter is presented and a thin film deposition technique for the paraffin is developed. S-parameter measurements of the fabricated phase shifters will be carried out by on-wafer probing and mechanical deflection profile of the micro-actuator will be measured.

ACKNOWLEDGMENT
This material is based upon work supported by the US National Science Foundation (NSF) under Grant No. 1408228. Authors would also like to acknowledge the staff members of the OSU Nanotech West Lab for their help with the fabrication.

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