Reconfigurable Millimeter-Wave Antennas Using Paraffin Phase Change Materials

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Abstract—We report, for the first time, a new class of reconfigurable antennas and RF microsystems developed using paraffin MEMS micro actuators. Paraffin is a phase change material that exhibits 15% volumetric (mechanical) change at approximately 70°C. Unlike traditional electrical phase-change materials (e.g. germanium telluride and vanadium dioxide) operating between quasi-dielectric and quasi-conductor states, paraffin is an organic low-dielectric-loss material (tan δ = 0.008, ε_r = 2.26 at 300 GHz) that undergoes reversible mechanical change. Here, we introduce low-loss thermo-electro-mechanically actuated MEMS capacitors at 100 GHz that are monolithically integrated with antennas. As a demonstration, a reconfigurable slot antenna with 6.7 GHz (92.6 – 99.3 GHz) of continuous frequency tuning is reported. It is also observed that the radiation pattern is not affected by the frequency reconfiguration and the maximum gain of the antenna is constant at 4.5 dBi for the entire frequency band. The proposed paraffin variable capacitors enable realization of wide variety of reconfigurable antennas as well as front-end components such as tunable oscillators at millimeter wave band.

I. INTRODUCTION

Designing antennas capable of dynamic reconfiguration of frequency, radiation pattern and polarization is crucial to fully utilize the millimeter wave (mmW) band. This band offers a wide frequency spectrum that promises high data rates for next generation cellular (73 GHz) [1] and short range wireless local-area networks (60–64 GHz) [2]. In addition, mmW has promising applications in imaging (94 GHz) [3], automotive anti-collision radars (77 GHz) [4], and all-weather radars. In all aforementioned applications, reconfigurable antennas are essential to enable frequency, spatial or polarization diversity in a single compact device to maximize the efficiency and flexibility of the mmW systems.

Reconfigurable antennas change their performance characteristics by modifying the current flow on antennas using diodes, switches, tunable materials, or mechanically movable parts. At microwave frequencies, variable capacitors based on p-i-n diodes and FET transistors are used. However, at mmW band these capacitors have high series resistance and exhibit significant losses. Microelectromechanical systems (MEMS) capacitive switches offer low insertion loss and high capacitance change [5]. Nevertheless, they only have two states of operation and are not capable of continuous tuning. Ohmic switches based on phase-change materials such as germanium-telluride [6] and vanadium dioxide [7] have low insertion loss, but similar to MEMS capacitors, they can only switch between high and low resistance states.

Here, for the first time, we present a reconfigurable antenna using novel paraffin-based MEMS capacitors. Paraffin is a low loss dielectric with a loss tangent of 8×10⁻³ at 300 GHz and relative dielectric constant of 2.26 [8]. Moreover, paraffin is a mechanical phase change material (PCM) that exhibits 15% volumetric change through its solid-liquid transition. It is in contrast to electrical phase change materials that operate between quasi-dielectric and quasi-conductor states. Paraffin PCM capacitors at 100 GHz that are monolithically integrated with antennas. As a demonstration, a reconfigurable slot antenna with 6.7 GHz (92.6 – 99.3 GHz) of continuous frequency tuning is reported. It is also observed that the radiation pattern is not affected by the frequency reconfiguration and the maximum gain of the antenna is constant at 4.5 dBi for the entire frequency band. The proposed paraffin variable capacitors enable realization of wide variety of reconfigurable antennas as well as front-end components such as tunable oscillators at millimeter wave band.

II. RECONFIGURABLE SLOT ANTENNA DESIGN

A. Slot Antenna Design

The proposed antenna design is shown in Fig. 1. Basic structure of the antenna is a bent slot line that has a high characteristic impedance and total length of λ/2 at resonance frequency. A similar antenna design was previously proposed by Behdad and Sarabandi where the slot antenna was loaded with two varactor diodes and tunability range of 1.1 – 2.94 GHz was achieved [9], [10]. In this paper we have replaced varactor diodes operating at 1 – 3 GHz with...
monolithically-integrated PPCM variable capacitors operating at 100 GHz.

Detailed side view of the antenna is shown in Fig. 2. Antenna substrate is 150-µm-thick quartz with relative dielectric constant \( \epsilon_r = 3.8 \). Width and length of the ground plane are 2.2 mm and 3 mm, respectively. Slot line has a total length of 1250 µm and has a characteristic impedance of 100 Ω. To extend the reconfiguration range, the lower part of the slot is designed to be wider to have a lower characteristic impedance. Slot line is bent to achieve maximum radiation at broadside similar to [9]. Antenna is excited by a open-circuited off-centered microstrip line. Position of the feed line and the open-stub length is optimized to have return loss better than 20 dB at all resonance frequencies.

A narrowband resonant slot antenna can be modeled as a \( \lambda/2 \) transmission line that is short circuited at the ends. When the structure is loaded with capacitors, resonance frequency of the antenna reduces. However, frequency shift depends on the position and the characteristic impedance of the slot line. Therefore to maximize the tuning range, position and dimensions of the capacitors are optimized. Transmission line model of the antenna is implemented in a circuit simulator to carry out the optimization. Initial values of \( C_1 \) and \( C_2 \) capacitors are estimated to be 19 fF and 12 fF, respectively.

B. Paraffin-Based MEMS Capacitor

In the proposed device, the change in capacitance is achieved using thermo-electro-mechanical actuation. The proposed variable capacitor employs a micro-heater embedded below a paraffin-held cavity capped with a deformable metal membrane. Depending on the heater-generated temperature, the paraffin expands reversibly and the distance between the membrane and ground changes. Doing so, a variable capacitor is formed between the metallic membrane and the ground plane.

To characterize the capacitance and loss characteristics of the PPCM capacitors, a coplanar waveguide (CPW) shunt variable capacitor is simulated. Geometry of the structure is shown in Fig. 3. Structure has a two RF ports and the variable capacitor is formed between the signal line and the deformable membrane. Series resistance and the capacitance values are extracted from the S-parameters. Thickness of the paraffin layer, \( h \), is varied from 1.7 µm to 2 µm. Fig. 4 shows the capacitance and resistance values for different paraffin thickness. According to Fig. 4(a), assuming 15% height change, approximately 15.4% change in capacitance is obtained. Fig. 4(b) shows that the series resistance of the capacitor is less than 0.13 Ω over the all frequency band of 80 – 120 GHz. Note that, conductive and dielectric losses contribute to the series resistance. To accurately simulate the dielectric loss, complex permittivity of the paraffin film was measured using terahertz time-domain spectroscopy technique in the frequency range of 0.3 THz – 1 THz. Preliminary results show that paraffin has a low dielectric loss of \( 8 \times 10^{-3} \) and relative dielectric constant is found to be 2.26 [8]. For simplicity complex permittivity values at 300 GHz is used in the model and electrical properties of the paraffin is assumed constant with respect to the mechanical phase change.

III. RESULTS

Full wave simulation of the antenna is carried out in HFSS. Initial paraffin layer thickness for \( C_1 \) and \( C_2 \) is considered to be \( h_1 = 3 \) µm and \( h_2 = 5 \) µm, respectively. Fig. 5 shows the return loss of the antenna for various thicknesses. According to this figure, resonance frequency of the antenna can be continuously tuned and it covers the frequency band of 92.6 – 99.3 GHz. Return loss is better than 10 dB for the entire
reconfiguration range. It can be seen that with decreasing height, the capacitance value increases, hence, the resonance frequency of the antenna decreases. Capacitance of the MEMS devices are estimated to be $C_1 = 17 \text{ fF}$ and $C_2 = 12 \text{ fF}$. Tuning range of MEMS capacitors are calculated to be 13.2% that resulted in a 6.7 GHz tuning range in operation frequency.

Radiation pattern of the antenna is plotted in Fig. 6. Antenna has a maximum gain of 4.5 dBi at broadside. Although it is not shown in the figure, radiation pattern of the antenna does not change over the tuning range and the gain of the antenna is approximately constant. E-plane radiation pattern ($\Phi = 0^\circ$) is asymmetric due to the asymmetric structure of the antenna along the y-axis (Fig. 1). However, H-plane radiation pattern, as expected, is symmetric due to the current distribution along lower and upper arm of the slot line.

IV. CONCLUSION

We presented, for the first time, a new class of reconfigurable antennas and RF systems using paraffin phase change materials. Electrical and mechanical properties of paraffin makes it an attractive material for designing low loss reconfigurable structures at mmW band. Moreover, thermo-electro-mechanically actuated paraffin devices can be monolithically integrated with RF front ends that reduces the fabrication complexities and power losses. In order to demonstrate potentials of PPCM RF microsystems, we presented a reconfigurable slot antenna using MEMS capacitors. PPCM capacitors were shown to have very low series resistance of 0.13 Ω at mmW band and capable of 15% capacitance change. Designed reconfigurable antenna has a tuning range of 6.7 GHz (92.6 – 99.3 GHz). Radiation pattern of the antenna is constant over the frequency range and maximum gain of 4.5 dBi was obtained for all resonance frequencies. For the future work, thermo-electro-mechanical actuation mechanism will be designed and multi-physics simulation of the structure will be carried out. After the monolithic fabrication of the antenna and the MEMS capacitors, actuation mechanism will be tested and antenna parameters will be measured.

REFERENCES


