Novel Paraffin-based 100-GHz Variable Capacitors for Reconfigurable Antennas

Behnam Ghassemiparvin, Spandan Shah and Nima Ghalichechian
Electroscience Laboratory, Dept. of Electrical and Computer Engineering
The Ohio State University, Columbus, Ohio, USA
Email: ghassemiparvin.1@osu.edu, ghalichechian.1@osu.edu

***Abstract*—We report multiphysics simulation results for paraffin variable capacitors integrated with bent slot antenna to form a frequency reconfigurable structure. Paraffin is a phase change material that its solid-to-liquid transition exhibits a 15% volumetric change. In addition to its mechanical properties, paraffin is an organic low-dielectric-loss material ($\tan\delta = 0.003$, $\epsilon_r = 2.26$ at 300 GHz) which is attractive for designing RF components at millimeter wave (mmW) band. Here, we introduce low-loss paraffin phase change material (PCM) capacitors at 100 GHz that are monolithically fabricated with antennas. A frequency reconfigurable slot antenna loaded with paraffin PCM capacitors is designed that is capable of continuous frequency tuning in the range of 97.5 GHz–103.5 GHz. The antenna has a maximum gain of 3.78 dBi and it is constant over the reconfiguration range. Actuation mechanism of the electrothermal actuator is analyzed in a multiphysics simulator. To characterize the deflection profile and the temperature distribution, it is crucial to fully couple the electric currents, heat transfer and solid mechanics. It is observed that with a 3 μm-thick actuation layer, 0.6 μm displacement can be obtained. A new fabrication method for the deposition of the thin paraffin film is developed and a fabrication process for the reconfigurable antenna is presented.**

***Index Terms*—Paraffin, phase-change material, reconfigurable antenna, MEMS, millimeter wave.**

I. Introduction

Millimeter wave (mmW) frequencies, due to their wide available spectrum, have become attractive for high data rate communication. High bandwidth at mmW frequencies enable emerging technologies such as next generation cellular (73 GHz) [1], short range wireless local-area (60–64 GHz) [2], and point-to-point wireless communication networks [3]. In addition, mmW band offers high resolution imaging (94 GHz) [4], automotive anti-collision radars (77 GHz) [5], and all-weather radars. In most of the aforementioned applications, reconfigurable antennas are essential to enable frequency, spatial or polarization diversity in a single compact device enhancing the efficiency and flexibility of the mmW systems.

Performance characteristics of antennas such as, input impedance, resonance frequency and radiation pattern can be reconfigured by modifying the current distribution using diodes, switches, tunable materials, or mechanically movable parts. At microwave frequencies variable capacitors based on p-i-n diodes and FET devices are used due to their high switching speed and acceptable quality factor. However, at mmW band these capacitors exhibit significant losses. Although there have been reports of mmW MEMS switches with low insertion loss [6], their operation is limited to two discrete states; therefore incapable of continuous tuning as needed in most applications. Ohmic switches based on phase-change materials such as germanium-telluride [7] and vanadium dioxide [8] exhibit low insertion loss, but similar to MEMS capacitors, they only operate in two states.

Here we introduce a reconfigurable antenna using novel paraffin-based MEMS capacitors. Paraffin is a low loss dielectric with a loss tangent of 3×10^{-3} at 300 GHz and relative dielectric constant of 2.26 [9]. Moreover, paraffin is a mechanical phase change material (PCM) that exhibits a 15% volumetric change through its solid-liquid transition. This is in contrast to electrical phase change materials that operate between quasi-dielectric and quasi-conductor states. The proposed PCM device employs a thermo-electro-mechanical actuation to control the temperature. Volumetric change of the paraffin enables continuous tuning of a variable capacitor. Paraffin-based MEMS capacitors—due to their low dielectric loss and continuous tuning—are very attractive for wide range of tunable RF components and reconfigurable antennas.

In the past, paraffin microactuators were mainly used in delivering force and stroke in micro-valves [10] and microactuator designs where large force is required [11]. In these designs only the hydraulic pressure (volume expansion) is used to generate mechanical force. In our work, in addition to the mechanical force, we take the advantage of the low dielectric loss of the paraffin to form low loss RF MEMS variable capacitors at mmW band.

In [12], for the first time, we have introduced a unique reconfigurable RF microsystem. The antenna structure was a microstrip-fed resonant slot line and the resonance frequency was shifted by loading the slot with paraffin PCM capacitors. Paraffin PCM capacitors are monolithically fabricated with the antenna which reduces the complexities of packaging and eliminates the losses due to wire bonds. The antenna design in [12] is improved by introducing a CPW feeding line that facilitates a single side fabrication and on-wafer probing. Moreover, antenna dimensions are optimized to obtain maximum tuning while maintaining a symmetric omnidirectional radiation pattern. For the electro-thermal actuation of the MEMS device, a multiphysics simulation model is developed. A fabrication process for the antenna is proposed and thin film deposition technique for the paraffin is developed.

This paper is organized as following. First, a reconfig-

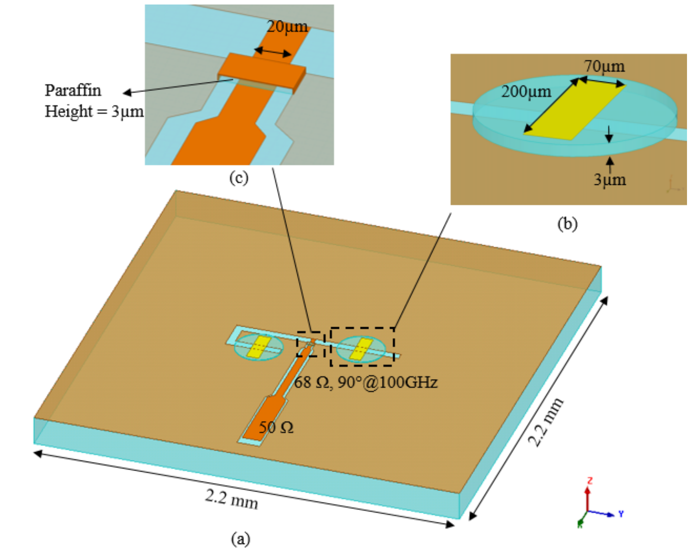

Fig. 1. (a) 3D view of the reconfigurable slot antenna with paraffin PCM capacitors, (b) detailed view of the paraffin PCM capacitor, and (c) detailed view of the bridge.

urable slot antenna is discussed. Subsequently, electrothermal actuation of the paraffin PCM device is described and the multiphysics simulation results are reported. Finite element simulation results and concluding remarks are discussed in Section IV and V, respectively.

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, operating at the second resonance frequency. In order to achieve frequency reconfiguration, the slot is loaded with monolithically integrated paraffin PCM capacitors. 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 [13] – [14]. In this paper we have replaced the varactor diodes operating at 1 – 3 GHz with monolithically-integrated PPCM variable capacitors operating at 100 GHz.

Antenna substrate is 150 μm-thick quartz with relative dielectric constant of $\epsilon_r = 3.8$. Ground plane is 2.2 mm×2.2 mm. Slot line has a total length of 1230 μm and it is bent to achieve maximum radiation at broadside similar to [13]. Antenna is excited by an off-centered CPW-line and coupled slot line modes are suppressed by introducing a ground equalizing bridge. Unlike the conventional airbridge design, this ground equalizing bridge is filled with paraffin in order to simplify the fabrication process.

A narrowband resonant slot antenna can be modeled as a λ-long transmission line that is short circuited at both ends. When the structure is loaded with capacitors, resonance frequency of the antenna decreases. However, frequency shift

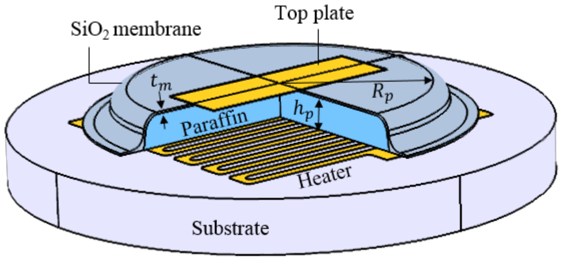

Fig. 2. 3D schematic of the electro-thermo-mechanical paraffin actuator with micro-heater, paraffin cavity and SiO_2 membrane.

depends on the position and the characteristic impedance of the slot line. Therefore to maximize the tuning range, slot line with a high characteristic impedance is chosen and capacitors are placed at locations where the electric field is the strongest.

B. Paraffin-Based MEMS Capacitor

Proposed paraffin PCM capacitor is a thermo-electro-mechanical actuator which mechanical movement is obtained by volumetric change in paraffin. As depicted in Fig. 2, the proposed variable capacitor employs a micro-heater embedded below a paraffin-held cavity capped with a deformable silicon dioxide (SiO_2) membrane. A metallic plate is placed on top of the membrane to form a capacitor between the top plate and the ground plane. 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 MEMS device, multiphysics simulation of the structure is carried out in COMSOL Multiphysics software. It is crucial to fully couple the interaction of the electric current through the heater and the heat transfer to the paraffin to simulate the thermal expansion and deflection of the membrane. The geometry of the device is shown in Fig. 2. Paraffin layer has a thickness and radius of 3 μm and 120 μm, respectively, and it is sealed with a 0.2 μm-thick silicon dioxide layer. The type of paraffin used as the actuation layer is pure Hexatriacontane ($C_{36}H_{74}$) and its density, heat capacity and thermal conductivity are plotted in Fig. 3 based on the measurement data given in [15] – [16]. According to Fig. 3, solid-phase transition temperature of Hexatriacontane is 345.1 K and the maximum volumetric expansion of 14.7% takes place in the transition region of 340 K – 360 K. Even though paraffin goes through a phase transition, it is assumed to be solid in all phases in the simulation. A meandered gold resistor with a thickness and width of 0.25 μm and 10 μm, respectively, is used as the heating source. The heater has an approximate resistance of 44 Ω. On the top boundary of the device heat convection with a rate of 5 W/m^2K is considered and all other outer boundaries of the geometry are set to be at room temperature. Stationary analysis is performed for various DC bias voltages. Center deflection of the membrane

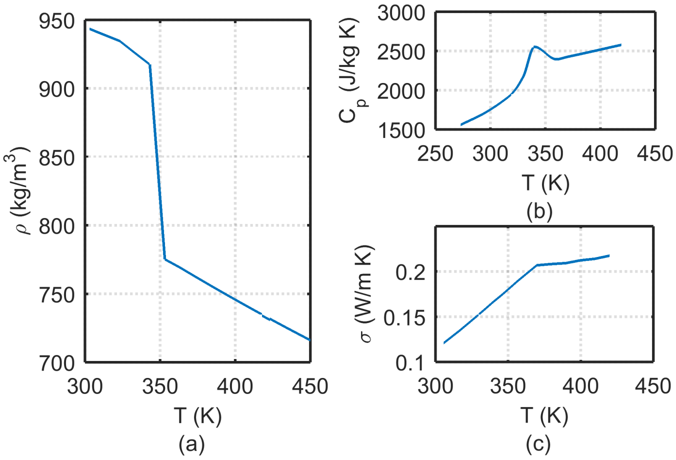

Fig. 3. Thermophysical properties of Hexatriacontane used in multiphysics simulation (a) density (b) heat capacity (c) thermal conductivity.

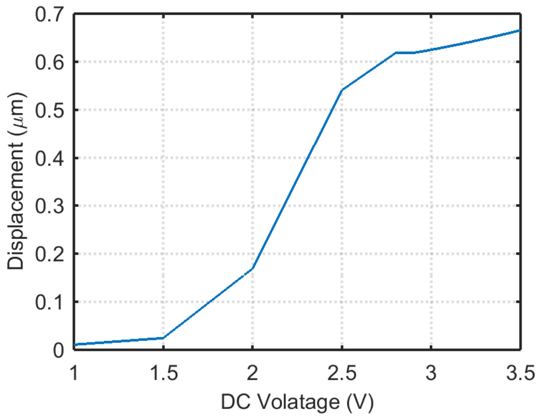

Fig. 4. Displacement of the actuator membrane (at the center) as a function of the bias voltage.

with respect to the voltage is plotted in Fig. 4 and it has a maximum deflection of 0.66 μm at 3.5 V. This corresponds to capacitance change of 15.7%. Temperature distribution of the actuator structure for DC voltage of 3.5 V is plotted in Fig. 5. Maximum temperature at the center of the membrane is 390 K and the temperature drops to 373 K at the edge of the paraffin layer.

III. Fabrication

Simplified process flow of the proposed reconfigurable antenna is depicted in Fig. 6. Fabrication is on a quartz glass substrate with 6 lithography steps. The antenna is fabricated by first patterning the metallic heaters on the quartz substrate followed by a vapor deposition of a 500 nm-thick SiO_2 insulation layer. This layer is used to insulate the heater form the slot antenna structure. Next, a Cr/Au (500/7000 Å) layer is evaporated and patterned which forms the ground plane. Then, the paraffin actuation layer is spin coated. The resulting thin film has a thickness of 3 μm and average roughness of 0.2 μm.

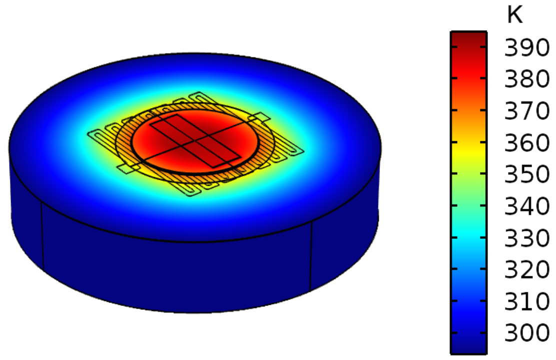

Fig. 5.Temperature distribution (units in K) of the actuator at DC bias voltage of 3.5 V.

After depositing paraffin all the subsequent steps should be kept below the melting temperature of the paraffin. To pattern the paraffin layer, first a Cr/Au etch mask layer is deposited. A 1.4 μm-thick photoresist is spin coated and soft baked at a lower temperature of 65°C for 45 minutes. After the exposure and development, the Cr/Au layer is wet etched. Then, the paraffin layer is patterned in an O_2:CF_4 plasma etcher. To form the top plate, after a low temperature lithography step, the Cr/Au layer is wet etched. For the sealing layer, 0.2 μm-thick SiO_2 layer is sputtered and patterned. Fabrication results of the device will be presented at the conference.

IV. Results

Full wave simulation of the antenna is carried out in ANSYS HFSS. The initial thickness of the paraffin is 3 μm and it is increased to 3.6 μm according to the displacement profile obtained from the multiphysics simulation. Fig. 7 shows the return loss of the antenna for various thicknesses. The antenna covers the frequency range of 97.5 GHz – 103.5 GHz and has a bandwidth of 1 GHz ($|S_{11}| < -10$dB). It can be seen that with decreasing height, the capacitance value increases, hence, the resonance frequency of the antenna decreases. In order to estimate the capacitance value of the MEMS devices, paraffin PCM capacitors are replaced by ideal sources and full wave simulation of the antenna is carried out. Next, s-parameters of the antenna is exported into the circuit simulator (ADS). By fitting the circuit simulator data to the full wave simulation, equivalent lumped element model of the MEMS capacitors is extracted. Lumped capacitance values of the MEMS device are given in Table I which indicates a capacitance change of 15.7% and it has a low series resistance of 0.06 Ω. As shown in Fig. 7 close agreement is achieved between full wave and circuit simulator.

The radiation pattern of the antenna is plotted in Fig. 8. The antenna has a omnidirectional pattern and has a maximum gain of 3.78 dBi at broadside. As shown in the figure, reconfiguring the frequency of the antenna does not significantly affect the radiation pattern and it is approximately constant over the tuning range.

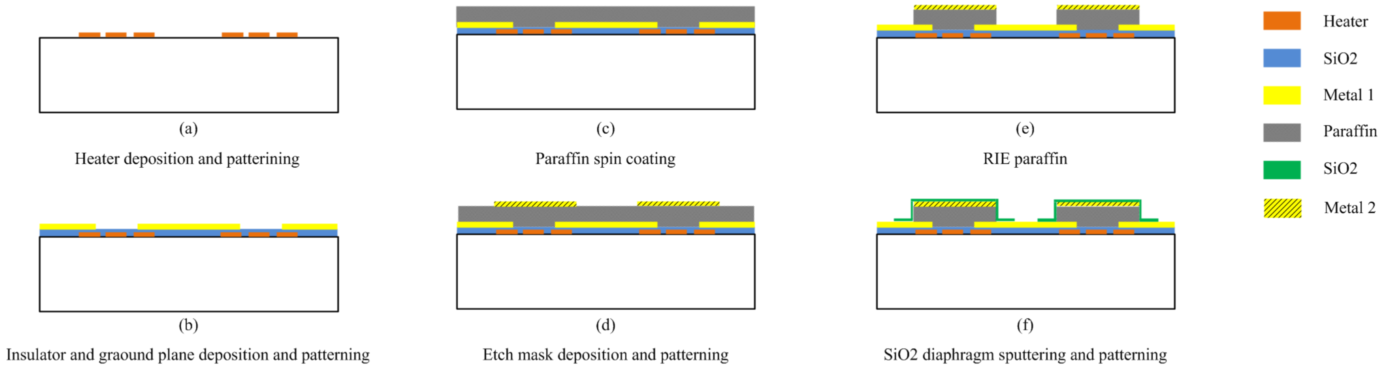

Fig. 6. Simplified fabrication process flow of the reconfigurable slot antenna.

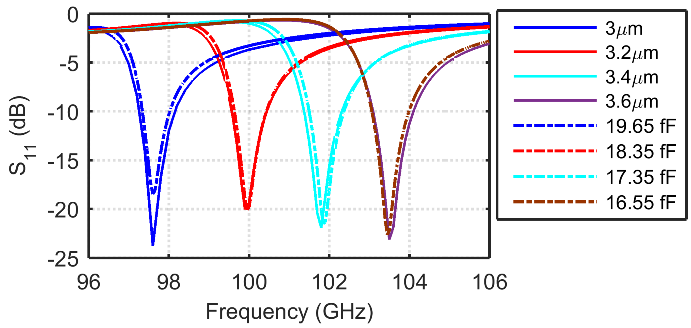

Fig. 7. Simulated S_{11} of the reconfigurable slot antenna for various paraffin thickness.

TABLE I
LUMPED CAPACITANCE OF PARAFFIN PCM CAPACITORS

Paraffin Height, h_p (μm)	C (fF)	R_{series} (Ω)
3	19.65	0.05
3.2	18.35	0.06
3.4	17.35	0.06
3.6	16.55	0.06

V. CONCLUSION

We presented, a new class of electrothermally actuated RF MEMS devices based on paraffin phase change materials. Electrical and mechanical properties of paraffin make it an attractive material for designing low loss reconfigurable structures at mmW band. Moreover, micromachining facilitates monolithical integration of paraffin PCM capacitors with antennas and RF components. Here, we reported a CPW-fed reconfigurable slot antenna using MEMS capacitors. The designed reconfigurable antenna has a tuning range of 6 GHz (97.5 – 103.5 GHz) and 1 GHz of bandwidth ($|S_{11}| < -10$dB). The radiation pattern of the antenna is constant over the frequency range and maximum gain of 3.78 dBi was obtained for all resonance frequencies. Fully coupled multiphysics simulation of the thermo-electro-mechanical actuation mechanism is carried out and it is shown that with

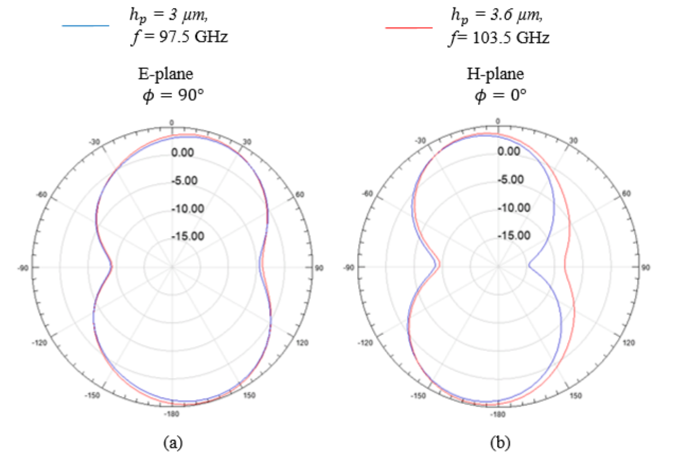

Fig. 8. Radiation pattern of the proposed antenna for paraffin thickness of 3 μm and 3.6 μm. Antenna has a maximum gain of 3.78 dBi.

a 3μm-thick paraffin film, 0.66 μm displacement can be achieved. Paraffin PCM capacitors are shown to have a very low resistance of 0.06 Ω and capable of 15.7% capacitance change. A fabrication process for the reconfigurable antenna is presented and a thin film deposition technique for the paraffin is developed. Electrical and mechanical measurement of the fabricated device will be presented at the conference.

ACKNOWLEDGMENT

This material is based upon work supported by the US National Science Foundation (NSF) under Grant No. 1408228.

REFERENCES

[1] S. Rangan, T. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[2] O. Andrisano, V. Tralli, and R. Verdone, "Millimeter waves for short-range multimedia communication systems," *Proceedings of the IEEE*, vol. 86, no. 7, pp. 1383–1401, July 1998.

[3] J. Wells, "Faster than fiber: The future of multi-G/s wireless," *IEEE Microwave Magazine*, vol. 10, no. 3, pp. 104–112, May 2009.

[4] L. Yujiri, M. Shoucri, and P. Moffa, "Passive millimeter wave imaging," *IEEE Microwave Magazine*, vol. 4, no. 3, pp. 39–50, Sep. 2003.

[5] J. Hasch, E. Topak, R. Schnabel, T. Zwick, R. Weigel, and C. Waldschmidt, "Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 3, pp. 845–860, Mar. 2012.

[6] J. Rizk, G.-L. Tan, J. B. Muldavin, and G. Rebeiz, "High-isolation W-band MEMS switches," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 1, pp. 10–12, Jan. 2001.

[7] L. Chau, J. G. Ho, X. Lan, G. Altvater, R. M. Young, N. El-Hinnawy, D. Nichols, J. Volakis, and N. Ghalichechian, "Optically controlled GeTe phase change switch and its applications in reconfigurable antenna arrays," in *Proc. SPIE-The International Society of Optical Engineering*, vol. 9479, Baltimore, MD, Apr. 2015.

[8] V. Sanphuang, N. Ghalichechian, N. K. Nahar, and J. L. Volakis, "Reconfigurable THz filters using phase-change material and integrated heater," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 4, pp. 583–591, July 2016.

[9] B. Ghassemiparvin and N. Ghalichechian, "Permittivity and dielectric loss measurement of paraffin films for mmW and THz applications," in *International Workshop on Antenna Technology (iWAT)*, Cocoa Beach, FL, Feb. 2016.

[10] E. T. Carlen and C. H. Mastrangelo, "Surface micromachined paraffin-actuated microvalve," *Journal of Microelectromechanical Systems*, vol. 11, no. 5, pp. 408–420, Oct 2002.

[11] J. S. Lee and S. Lucyszyn, "A micromachined refreshable braille cell," *Journal of Microelectromechanical Systems*, vol. 14, no. 4, pp. 673–682, Aug 2005.

[12] B. Ghassemiparvin and N. Ghalichechian, "Reconfigurable millimeter-wave antennas using paraffin phase change materials," in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, April 2016, pp. 1–4.

[13] N. Behdad and K. Sarabandi, "A varactor-tuned dual-band slot antenna," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 401–408, Feb. 2006.

[14] ——, "Dual-band reconfigurable antenna with a very wide tunability range," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 409–416, Feb. 2006.

[15] Y. Jin and B. Wunderlich, "Heat capacities of paraffins and polyethylene," *The Journal of Physical Chemistry*, vol. 95, no. 22, pp. 9000–9007, 1991.

[16] E. T. Carlen, "Electrothermally actuated paraffin microvalves," Ph.D. dissertation, Dept. of Electrical Engineering, University of Michigan, Ann Arbor, MI, 2001.