A Tunable Capacitor Using An Immiscible Bifluidic Dielectric

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Abstract **— A tunable capacitor using two immiscible fluids of different dielectric constants as a dielectric material are investigated and the feasibility of its RF application is demonstrated. Large capacitance change is obtained when the two fluids have large differences of dielectric constant. When deionized water and air are used as the two fluids, the tunability ($T[\%]=100\times(C_{water}-C_{air})/C_{air}$) shows a maximum of 6700% at low frequency. Silicone oil (dielectric constant of 2.5) and air is used for the high frequency application to ensure low dielectric loss in the RF frequency range. Nominal tunability and Q-factor at 2.5GHz is 15.7% and 17.4, respectively. Barium strontium titanate (BST) nano powder mixture with silicone oil (43 wt% of BST) shows 12% more tunability than that of a pure silicone oil capacitor (due to the high permittivity contribution of BST) without concomitant Q-factor degradation. A tunable resonator consisting of the fluidic tunable capacitor combined with a line inductor is fabricated and a tuning bandwidth of 15% (0.27GHz) is obtained at 1.8GHz.**

I. Introduction

A tunable capacitor is one of the fundamental components in various wireless applications, such as a tunable filter, a voltage controlled oscillator (VCO), a matching network, and a phase shifter. Currently prevailing tunable capacitor technologies include a semiconductor diode varactor, a ferroelectric varactor, and a microelectromechanical systems (MEMS) based varactor [1] [2] [3].

Among them the MEMS tunable capacitor benefits from its high Q-factor from inherent low dielectric loss through the air gap although it has relatively low tunability [4]. Recently, many efforts have been made to increase the tunability of these devices, including geometrical modifications such as multiple parallel plate capacitor approaches [5, 6]; high-aspect-ratio interdigital capacitors [7]; and dielectric fluid immersion capacitors [8]. These MEMS tunable capacitors, however, commonly use a homogeneous dielectric fluid as a dielectric material i.e. either air or oil, and have movable electrodes for the tuning, thereby ultimately limiting tunability by achievable geometric displacement.

In this paper, a microfluidic tunable capacitor, which relies on the motion of dielectric fluids as opposed to geometric variation, is presented. This capacitor has electrodes implemented within a microfluidic channel, and provision for flowing two immiscible dielectric fluids (e.g., two immiscible liquids or a gas/liquid combination) through the microchannel, thereby electrically interacting with the embedded electrodes. This approach has two major advantages. First, since the capacitance change in this device is affected by both the dielectric constant difference of two fluids and by fluidic displacement, large tunability can be obtained by choosing two fluids with a large permittivity difference. Tunability can be controlled precisely by utilizing a long electrode embedded channel path. Second, because the moving part is the fluid and not solid electrodes as in other MEMS capacitors, long life time reliability is expected.

The first part of this paper discusses the device concept and preliminary test with the fluidic tunable capacitor and the second part demonstrates its application to a tunable resonator.

II. Tunable Capacitor Using Dielectric Fluid

A. Concept

Two parallel metal plates, which have a width w, a length L, and a gap d, are filled with two immiscible fluids having different dielectric constant, ε_1 and ε_2 in Figure 1. Assuming fluid 1 moves from the left to the right, the total capacitance when the interface of the two fluids is at x is described in Equation (1):

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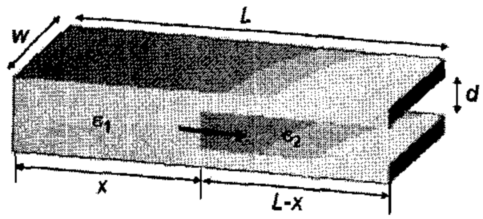

Fig 1. Schematic of the bifluidic capacitance model

$$C(x) = \frac{\varepsilon_0 \varepsilon_1 x w}{d} + \frac{\varepsilon_0 \varepsilon_2 (L - x) w}{d} \qquad (1)$$

The degree of capacitance change can be expressed as a percentage tunability T as a function of x as equation (2):

$$\begin{aligned} T(x)[\%] &= \frac{C(x) - C(0)}{C(0)} \times 100 \\ &= \left(\frac{\varepsilon_1}{\varepsilon_2} - 1 \right) \frac{x}{L} \times 100 \end{aligned} \qquad (2)$$

The tunability is proportional to the interface position x and the dielectric constant ratio of the two fluids ($\varepsilon_1/\varepsilon_2$) when $\varepsilon_1/\varepsilon_2$ is much greater than unity. Large tunability is therefore obtained by choosing two fluids having a large dielectric constant difference.

B. Experimental

To verify the device concept, gap capacitor architecture is employed instead of a parallel capacitor approach due to fabrication simplicity. Figure 2 shows a schematic of the gap capacitor while Figure 3 shows a device fabricated on a glass substrate using standard micromachining approaches. The wall and the channel cap are made from transparent polydimethylsiloxane (PDMS) for observation convenience. The length, the width, and the height of the channel, and the gap between electrodes, are 5mm, 600μm, 400μm, and 200μm, respectively.

Deionized water and air are chosen as the two dielectric fluids because they are immiscible and the dielectric constant ratio is approximately 80 ($\varepsilon_{water} \cong 80$ and $\varepsilon_{air} \cong 1$). When deionized water flows through the channel, the resultant interelectrode capacitance as a function of normalized relative position x/L of the meniscus between water and air is shown in Figure 4, measured at 1 kHz. The capacitance change is linearly proportional to the

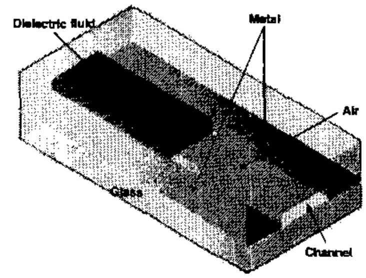

Fig 2. Schematic of a gap capacitor

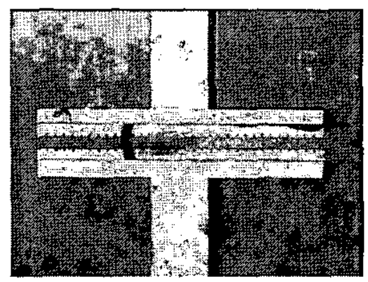

Fig 3. A fabricated gap capacitor with 33% of silicone oil filled

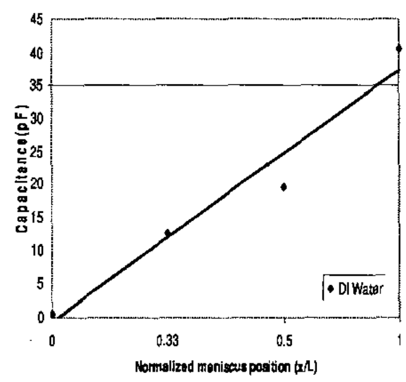

Fig 4. Capacitance according to meniscus position
* The solid line is obtained from linear least square method

position x as expected in Equation 1. The slope is not exactly the same as in Equation 1 because the capacitor under test is not a parallel plate capacitor, as well as due to susceptance field leakage effects. The maximum tunability is 6700% when the electrodes are completely covered with water. (where C_{air}: 0.6pF, C_{water}: 40.6pF). Although this device clearly demonstrates the potential of this approach, water, even when deionized, forms a lossy dielectric at many RF frequencies of interest, and therefore may not be appropriate for many applications.

For applications in the RF frequency range, a bifluidic combination of silicone oil and air is used. While silicone oil has a lower relative dielectric constant of 2.5 (compared to over 80 for water), it also possesses an extremely low loss tangent (which should translate to high Q-factor) even at RF frequencies.

In an attempt to increase the relative dielectric constant of this fluid while maintaining low dissipation, Barium Strontium Titanate (BST) nanoscale powder is mixed into the silicone oil. Three different silicone oil-BST mixtures were prepared with 20, 33, and 44 weight percent of BST.

The measurements are carried out at 2.5GHz after a standard SOLT calibration with an HP8510 vector network analyzer. The Q-factor is measured and the effective dielectric constant is extracted using the measured data and the numerical analysis with ANSYS 7.0. As the amount of BST in the silicone oil was increased, the capacitance was also increased due to the increase of dielectric constant of the liquid. The results are summarized in Table I. The relatively low Q-factor of the air dielectric reflects measurement limitations; Q-factors in Table I for loaded and unloaded oils should be interpreted in comparison to the air figures. It can be seen that there is a degradation of Q-factor of 10-15% over air due to the presence of the oils.

Table I. Summary of Measured Capacitance and Q-factor at 2.5GHz

	Capacitance [pF]	Q-factor	Tunability [%]	ε_r*
Air	0.382	20.3	-	-
Silicone oil (100CTS#)	0.442	17.4	15.7	2.5
20% BST +Oil	0.454	18.8	18.9	2.9
33% BST +Oil	0.470	17.7	23.0	3.2
43% BST +Oil	0.488	17	27.8	3.4

*An effective dielectric constant calculated from measurement data and ANSYS 7.0 simulation.

CTS stands for centistokes, a unit of viscosity.

III. RESONATOR USING DIELECTRIC FLUID

A. Design and Fabrication

The previous tunable capacitor has a fluidic channel only above the electrodes. In order to achieve more tunability, an additional channel underneath the electrodes is formed in Figure 5. The upper and lower channels consist of PDMS and the electrode is copper. The total channel height, width, electrode gap, and electrode thickness are 630μm, 300μm, 100μm, and 30μm, respectively.

The channel and the metal parts were fabricated separately and assembled. Photodefinable epoxy, SU-8 (Microchem, Inc.) is patterned by standard photolithography for the channel mold (a). PDMS was poured and cured to form channel structure (b). Metal electrodes are fabricated by laser cutting of 30μm thick copper sheet. Fabrication is completed by glue-bonding parts (c).

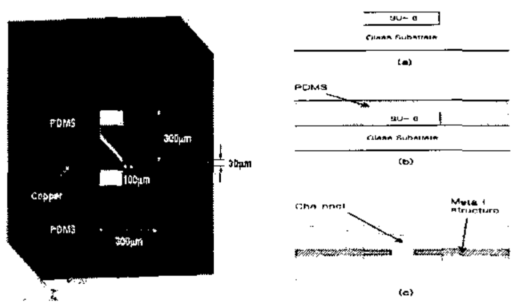

Fig 5. Channel geometry and fabrication process

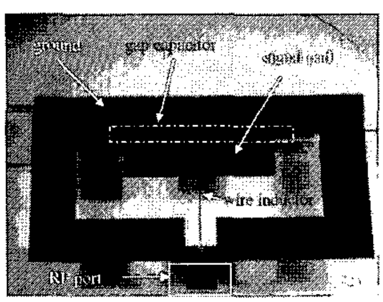

Fig 6. Fabricated fluidic tunable resonator

B. Testing and Results

Figure 6 shows a fabricated structure before bonding the top portion of channel. Two sets of electrodes are made of copper and stainless steel. Silicone oil (100 CTS) and air are used as two dielectric fluids. In this experiment, BST nanopowder is not added. One port s-parameter is measured in the frequency range of 50 MHz to 3 GHz. A Smith chart of the s-parameter is shown in Figure 7. When the channel is completely filled with the oil, (x/L=1), the resonant frequency decreases due to higher capacitance from the high dielectric constant fluid. A slight increase in the Q-factor is observed.

Extracted capacitance according to frequency is plotted

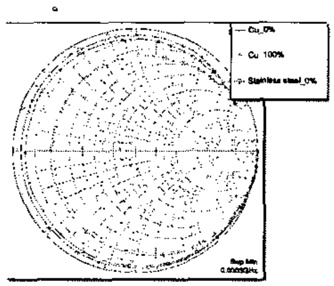

Fig 7. Smith chart of tunable resonator, 50MHz - 3GHz.

in Figure 8. As for the copper electrode resonator, the maximum tunability is approximately 38% and the corresponding tuning bandwidth is 15% (0.27 GHz) at 1.80 GHz (at x/L=0) to 1.53 GHz (at x/L=1). Extracted lumped paramter elements are shown in Table II.

Table II. Lumped parameters of series RLC equivalent ckt

	x/L	C [pF]	T [%]	L [nH]	ESR [Ω]	SRF [GHz]	Q*
Copper	0	1.27	0	6.2	2.70	1.80	25.8
electrode	1	1.75	38	6.2	1.81	1.53	33.0

ESR: equivalent series resistancce
SRF: self resonance frequency ($\equiv f_0$)
* Q-factor is defined as $1/\omega_0 RC$, where $\omega_0 = 2\pi f_0$

V. Conclusion

A tunable capacitor using two immiscible fluids flowing through a microfluidic channel is demonstrated. High tunability is obtained when two fluids with large dielectric constant difference are chosen. Deionized water and air system shows the maximum 6700% tunability. As for RF applications, a silicone oil / air system is implemented. A tunable capacitor shows relatively low tunability due to

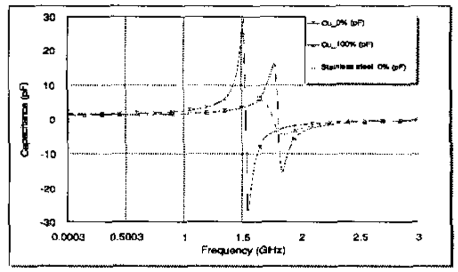

Fig 8. Capacitance as a function of frequency.

low permittivity difference between oil and air, but BST-oil composite shows a tunability improvement due to the permittivity contribution of BST nanopowder. A tunable resonator consisting of oil/air pair and copper electrodes shows 38% tunability and 15% (0.27GHz) resonance frequency shift obtained at 1.8GHz to 1.53GHz. As for the ideal RF application, fluids with both large permittivity and low RF loss are desirable.

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