Microwave Characteristics of Liquid-Crystal Tunable Capacitors

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***Abstract*—This letter investigates the microwave characteristics of the liquid crystal tunable capacitors for the first time. With the dielectric anisotropy properties, the liquid crystal capacitors present very different characteristics compared to the semiconductor or MEMS tunable capacitors. A quality factor of 310 with a control voltage of 5 V was achieved at 4 GHz. A tuning range of 25.3% for the control voltages from 0 to 5 V was obtained at 5 GHz. The results demonstrate the potential applications of liquid crystals as dielectric materials for capacitors with high quality factors and wide tuning ranges at high frequencies, particularly suitable for the future flexible electronics with transparent substrates.**

***Index Terms*—Liquid crystal, microwave, tunable capacitors.**

I. Introduction

FLEXIBLE display and electronics are emerging to play a great impetus on daily life of human beings in the near future. Liquid crystals have been employed for flexible display for decades because of their transparency, flexibility, birefringence, and dependence of refractive index on voltage. Given the above properties, the liquid crystals have tremendous potential for tunable devices used in the microwave frequency range. Recently, the liquid crystals were demonstrated in the applications of microwave phase shifters, microwave delay lines and microwave wavelength selectors [1]–[6]. However, utilizing the special property of the dielectric anisotropy $(\varepsilon_{||} \neq \varepsilon_{\perp})$ for microwave tunable capacitive devices has not been explored in the above studies. Since dielectric constants of liquid crystals are voltage-dependent, the liquid crystal based capacitors could be ideal for varactor-type devices. Hence, such intrinsic properties make liquid crystals excellent candidates for the emerging flexible electronics technology, in particular for transparent applications.

In this paper, liquid crystal tunable capacitors for microwave applications were designed and characterized for the first time. The devices were fabricated on glass substrates with fractal conductive structures made of gold. The devices exhibit bias-dependent C–V characteristics in a wide frequency range. The quality factor Q strongly depends on control voltage and on frequency; this characteristic is very different from semiconductor or MEMS varactors. This paper is comprised of the device design, characterization, extraction of quality factor, and finally, analysis and discussion of experimental results.

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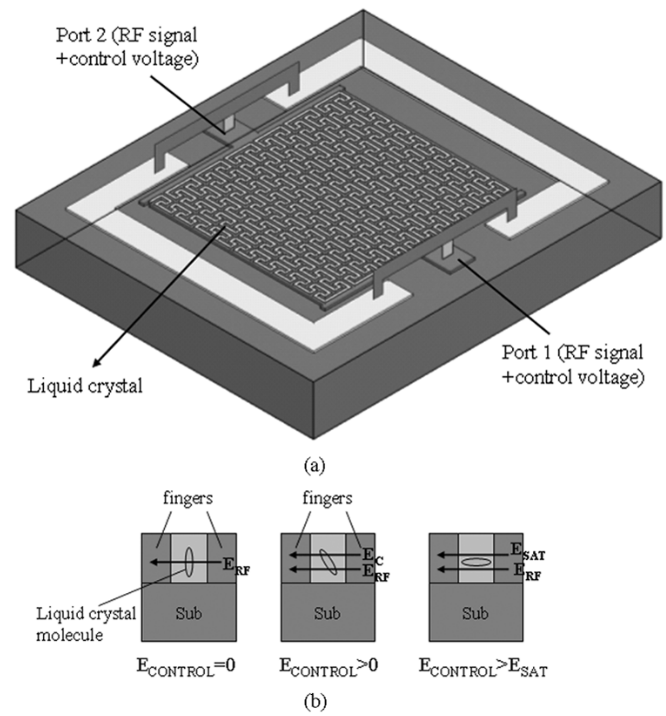

Fig. 1. (a) Schematic of fractal-type liquid crystal tunable capacitor, (b) Operation principle of liquid crystal molecule with applied electric field.

II. Device Design

Fig. 1(a) reveals the schematic of tunable capacitors in this letter. The liquid crystal E7 is injected into the gaps between fractal structure fingers. The operation principle of the liquid crystal tunable capacitors is illustrated in Fig. 1(b). Control voltage signals are embedded in RF signals to adjust capacitances. As the control voltages (i.e., electric field intensity) increase, liquid crystal molecules are forced to align more parallel to electric field lines by electrostatic dipole moments applied. Hence, the dielectric constants of the liquid crystal change continuously from perpendicular dielectric constant $\varepsilon_{\perp}$ toward parallel dielectric constant $\varepsilon_{||}$. The difference of $\varepsilon_{||}$ to $\varepsilon_{\perp}$ intrinsically results in the upper bound of tuning range of capacitances.

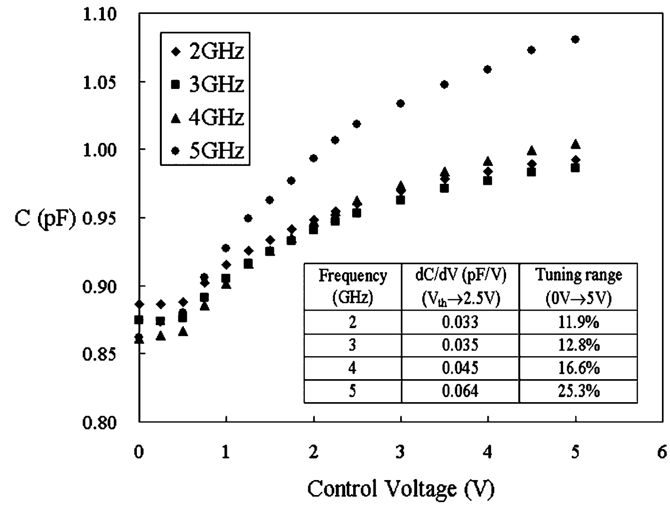

Fig. 2. Measured capacitances versus control voltage for 2, 3, 4, and 5 GHz ($V_{\rm th}$ denotes threshold voltage).

The liquid crystal tunable capacitors were fabricated on the glass substrates with gold metal lines on top. The fingers of the tunable capacitors under test are 5 and 4 μm in width and in thickness, respectively. The gap spacing between two adjacent fingers is 5 μm. The devices are 500 by 500 μm from the top view.

III. Device Characterization and Discussion

On-wafer measurement of the tunable capacitors was conducted using a performance network analyzer Agilent E8364B with coplanar ground-signal-ground (GSG) probes. The parasitic effect of probing pads was de-embedded to extract capacitances using the lumped-element single-π model [7].

$$C = -\frac{\text{Im}[Y_{21}]}{2\pi f} \tag{1}$$

where Im and f denote the imaginary part of Y-parameter and operation frequency, respectively. The experimental results of capacitances as a function of voltages at different frequencies were plotted in Fig. 2. The devices without liquid crystal, for reference check, were measured to have a constant capacitance value of 0.52 pF at voltages of 0–5 V at 5 GHz. A threshold voltage ($V_{\rm th}$) was estimated to be about 0.75 V in the devices with liquid crystal injected. Beyond the threshold voltage, capacitances were found to vary with voltages (V_B) at all frequencies tested. For instance, the change of capacitance per volt ($V_{\rm th} \rightarrow 2.5$ V) at 5 GHz is 64 fF/V and the tuning range is 25.3% from 0 to 5 V.

The threshold voltage can be interpreted using elastic continuum theory of liquid crystals [8]. The net free energy (F) is the sum of contributions from deformation of liquid crystal molecules and external control voltages (i.e., electric fields). The liquid crystal director distribution tends to orientate with respect to the electric fields to minimize the net free energy. Therefore, the threshold voltage can be calculated using (2).

$$V_{\rm th} = \pi \left(\frac{k_{\rm ii}}{\varepsilon_0 \cdot \Delta\varepsilon} \right)^{1/2} \tag{2}$$

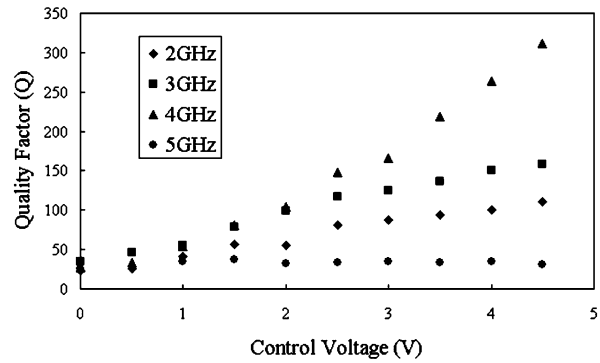

Fig. 3. Measured quality factor (Q) versus control voltage for 2, 3, 4, and 5 GHz.

where ε_0 is the permittivity in free space, $\Delta\varepsilon$ is the dielectric anisotropy ($\Delta\varepsilon = \varepsilon_{||} - \varepsilon_{\perp}$) and $k_{\rm ii}$ is the elastic constant of liquid crystal. Given $\Delta\varepsilon = 13.8$ and $k_{\rm ii} \approx k_{11} = 11 \times 10^{-12} N$ for E7, the threshold voltage is estimated to be 1 V, which is slightly larger than the experimental results. This difference results from the semi-hard boundary condition of the liquid crystal in the devices tested. The hard boundary requires the tilt angle of liquid crystal directors at the boundaries independent of electric fields applied. Equation (2) is derived based on hard boundary condition while the devices tested have one surface exposed to air (i.e., not fully confined.) Hence, the measured threshold voltage was lower than prediction. Also, note that the tuning range at 5 GHz is larger than those at 2, 3, and 4 GHz. This could be caused by dependence of the dielectric anisotropy $\Delta\varepsilon$ on operation frequencies. This issue is currently under investigation.

Experimental Q values (i.e., energy stored divided by energy loss) versus control voltages for different operation frequencies were illustrated in Fig. 3. At 2, 3, and 4 GHz, the Q values increase as the control voltages turn up. Enhancement of the Q values due to increment of the control voltage results from the dielectric anisotropy of liquid crystal, including the component of the loss tangent perpendicular to the electric field applied ($\tan\delta_{\perp}$) and the parallel component ($\tan\delta_{||}$) The value of $\tan\delta_{\perp}$ is larger than that of $\tan\delta_{||}$ in the GHz range [4]; therefore, the Q values enhance when liquid crystal molecules gradually orientate toward the states parallel to the electric fields under increasing control voltages. Further, the Q values remain invariant at 5 GHz despite change in control voltage. The cause of such behavior is unclear; it could be the frequency dependence of dielectric constants.

In terms of operation frequencies, the Q values reach the maximum at a frequency between 4 and 5 GHz. In the gigahertz range, dielectric losses ($\tan\delta_{\perp}$ and $\tan\delta_{||}$) decrease at the operation frequencies beyond the resonant frequencies of $\tan\delta_{\perp}$ and $\tan\delta_{||}$ [4], leading to higher Q values for higher frequencies. When the operation frequencies reach 5 GHz, the Q values become smaller because of ohmic loss in metal lines and dielectric loss in liquid crystal. At 5 GHz, the skin depth of gold is calculated to be 1.2 μm, limiting the effective conductive area of the metal lines with the cross section of 4 by 5 μm. In addition, the frequency dependence of the dielectric constants at microwave range is still under investigation.

IV. CONCLUSION

In this letter, a new type of tunable capacitors using liquid crystal as tuning media were proposed and characterized for the first time. The tuning mechanism of the capacitors is achieved based on dielectric anisotropy of liquid crystals. The devices exhibit bias-dependent C–V and Q–V characteristics in a wide frequency range. The Q values are influenced by ohmic loss of metal line and by dielectric loss in liquid crystal. The frequency dependence of the dielectric constants in liquid crystal is currently under investigation.

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