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Full Length Research Paper

Design and simulation reconfigurable liquid crystal patch antennas on foam substrate

S. Missaoui[1]*, A. Gharbi[1] and M. Kaddour[2]

[1]Electronics Laboratory, Department of Physics, Faculty of Science, Tunis El Manar, Tunisia.
[2]Sfax Faculty of Science, Tunisia.

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In this article, the use of liquid crystal-based patch antenna is proposed. A first test device was, therefore, conceived in planar technology with a low-cost foam substrate. In order to have a reduced antenna structure, we have studied an antenna miniaturized by inserting slots. Moreover, the use of liquid crystal in the design of patch antennas allows adjustment of the resonance frequency. To benefit from liquid crystal anisotropy and thus obtain agility, the antenna response is modified by means of an external static electric field that tells on dielectric permittivity of the liquid crystals. The simulated results of the devices are compared with measured data, and good agreement is obtained.

Key words: Liquid crystals, patch antenna, agile structure, microwave.

INTRODUCTION

Wireless communications systems have growth drastically in the last years. For this reason, multifunction antennas have been developed to achieve multiple operation over several wireless services. The patch antennas used, for example, in portable equipment sometimes need to satisfy severe constraints on physical dimensions, and the need for miniaturization is called for. The antenna microstrip enjoy many advantages over their counterparts, such as low manufacturing cost via modern printed circuit technology, low profile, ease of integration with monolithic microwave integrated circuits (MMICs) (Thompson et al., 2006) and integrated passives, and the ability to be mounted on planar (Schussler et al., 2004), nonplanar, and rigid exteriors (Pozar, 1992). When designing planar antennas for wireless communications, it becomes necessary to have a microstrip antenna that is compact in size and able to be integrated with other devices. Up to now, several approaches have been proposed to study the patch antenna (Martin et al., 2005, 2004, 2003; Reed et al., 2001). One of the sought properties for this device is the possibility of external control. For decades, to achieve this objective, enormous efforts have been deployed for using new materials which have a better functionality. Among these materials, liquid crystals (LCs) (Dolfi, 1993; Zakharov and Mirantsev, 2003) are potentially useful. This material consists on a state of matter which has properties between those of a conventional liquid and those of solid crystals. In the nematic state, the rod like molecules float around as in a liquid phase however these are ordered in their orientation. Nevertheless, recent studies (Missaoui et al., 2011, 2010; Mueller et al., 2004; Splingart et al., 2001) have shown their dielectric anisotropy property. This property can be deduced from a permittivity tensor, depending on the direction of the applied electric field. The relative dielectric constant of a nematic LC can be changed by orienting the director of LC molecules relative to the excited radio frequency field polarization with an electro-static field.

In this paper, we propose patch antenna foam substrate using planar technology based on LCs materials. This choice allows the LC anisotropy property controlled by an electric field. We will compare the changes in frequency resonance caused by application of a DC voltage to two antennas of similar size, but containing LCs of different anisotropy. Finally, we will deal with the patch antenna size reduction realized by engraving inductive slots on the patch with the same requirement as above for the resonance frequency. Numerical results are compared with the existing data (Martin et al., 2003) to confirm the accuracy of the proposed analysis.

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*Corresponding author. E-mail: sayed.elmissaoui@gmail.com

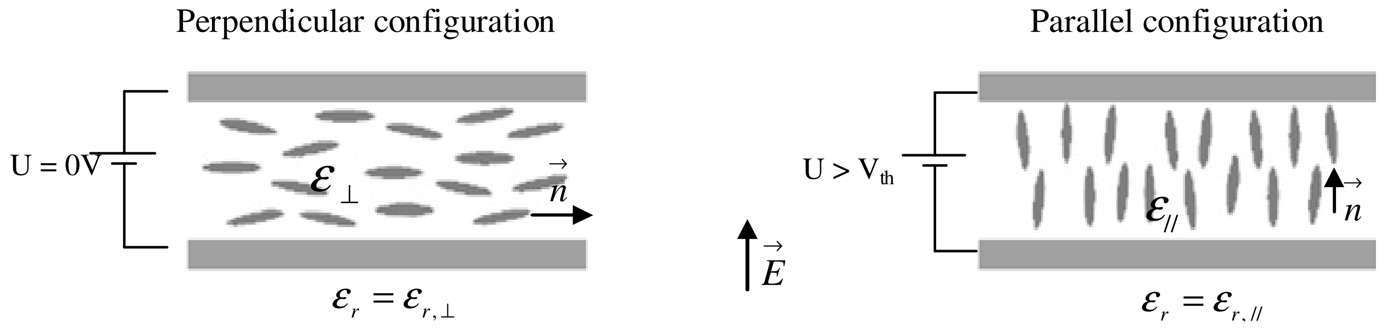

Figure 1. Configuration permittivities $\varepsilon_{r//}$ and $\varepsilon_{r\perp}$.

PROPERTIES OF LIQUID CRYSTALS

LCs is an anisotropic material showing both properties of a crystal and a liquid. All further explanations are related to nematic LCs which shows up to now the best dielectric properties at microwave and millimeter-wave frequencies. LC can be processed around 300℃, has excellent electrical properties, very low moisture absorption, light weight, mechanical stiffness, thermal stability (CTE = 0 to 30 ppm/℃), chemical resistance. Depending on the temperature, LC phase exists in a mesophase between a crystalline solid and an isotropic liquid. In this state, the material can flow like a liquid but at the same time, molecules have orientational order. The size of the molecule is typically a few nanometers. For this configuration, the electrical parameters of the LCs are defined as $\varepsilon_{\perp}$ and $\tan\delta_{\perp}$. The molecules can be rotated parallel to the RF field by applying a voltage between the conductors in order to create an electrostatic field in the LCs, thus changing the value of the permittivity and loss tangent to $\varepsilon_{//}$ and $\tan\delta_{//}$ respectively. The orientation with electric field is schematically presented in Figure 1.

The dielectric anisotropy is defined as:

$$\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp} \tag{1}$$

and, analogously for the relative permittivity:

$$\Delta\varepsilon = \varepsilon_{r,//} - \varepsilon_{r,\perp} \tag{2}$$

The anisotropy can be positive or negative. All nematic LCs used in this work exhibit positive anisotropy. Therefore one can consider that the agility in frequency is a new application of these materials. The dielectric anisotropy of LC is very suitable for phase shifting purposes, since the change in permittivity is associated with a corresponding change in the phase of a wave propagating through the LC. Therefore, the most investigated applications for LCs at microwave frequencies were patch antennas devices.

SURVEY AND SIMULATION RECTANGULAR PATCH ANTENNA TO BASIS OF THE LIQUID CRYSTALS

Presentation of the rectangular patch antenna

A prototype nematic LC structure of high dielectric anisotropy from 2.7 to 2.9 is given by K15 (5CB) of Merck (Splingart et al., 2011). Then, focus will be on the dimensional requirements for the rectangular patch antenna in order to get a resonance frequency at 5 GHz. The geometry to be considered (Figure 2) consists to three elements: The ground plane, the 500-µm-high cavity realized with 500-µm-thick foam to house the capillarity-inserted LC, and the patch (Martin et al., 2003). Due to the close similarity of the dielectric constants of foam ($\varepsilon_r = 1.07$, $\tan\delta = 10^{-3}$) and air, the wave propagation is not affected, and thus the produced R.F. field is more concentrated in the LC. Application of a DC voltage to the feed line produces antenna agility. We arbitrarily set the resonance frequency to 5 GHz, which required a 20.7 × 21 mm rectangular patch antenna; these dimensions are issued from simulations.

Figure 3 shows the design of the rectangular patch antenna dimensions based on LC. To get a 5-GHz resonance frequency, the patch antenna must be a 20.7 × 21 mm rectangle, with a cavity height and foam thickness of 500 µm. Resonance frequencies was varied through a superposition DC voltage to the microwave field.

SIMULATION RESULTS

In a first step, the HFSS (High frequency structure simulator), designed antenna was simulated to determine the patch size at a 5 GHz resonance frequency. Figure 4 shows that agility was obtained by varying the LC dielectric permittivity, established by dielectric characterisation, from 2.7 to 2.9. The simulated return loss is centred around 5 GHz. It can be seen that the return loss achieved -30 Db from 4.5 to 5.5 GHz. The resonance frequency variation (ΔFr) is 115 MHz, corresponding to a

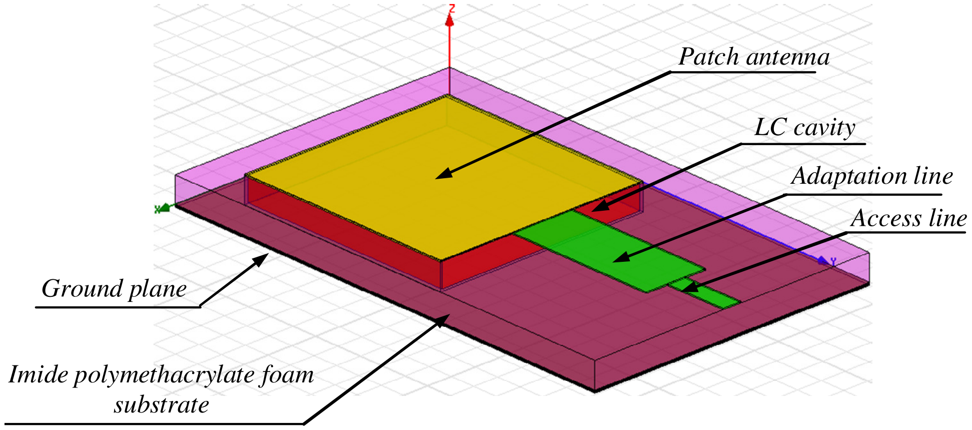

Figure 2. Design of the rectangular patch antenna (*HFSS*).

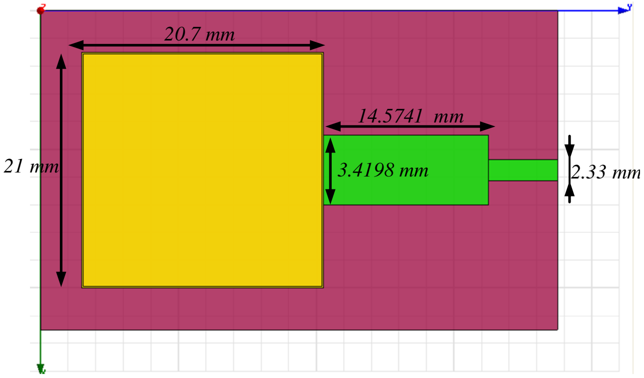

Figure 3. Rectangular patch antenna dimensions.

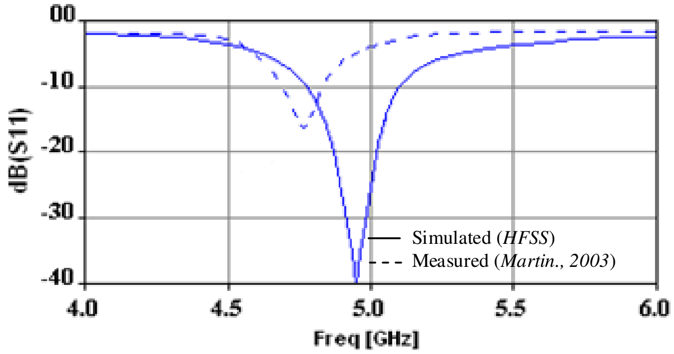

Figure 5. Simulated and measured return losses without applied DC voltage.

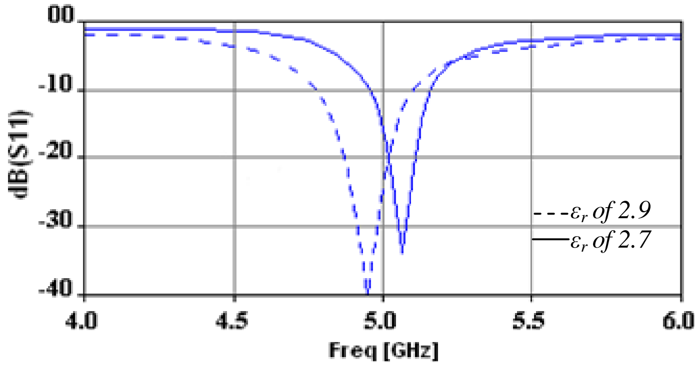

Figure 4. Simulated return losses for two different permittivities by (HFSS).

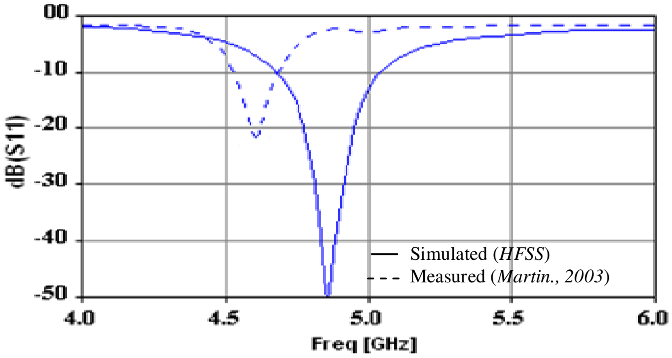

Figure 6. Simulated and measured return losses with applied 20 V DC voltage.

frequency agility of 2.3%.

Figures 5 and 6 depict the results of simulated and measured return losses with and without applied DC voltage and the dielectric permittivity liquid crystal is 2.9. It can be seen from Figure 5 that the simulated return loss achieved -30 dB from 4.5 to 5 GHz and the measured return loss achieved -10 dB from 4.5 to 5 GHz. The resonance frequency variation (ΔFr) between simulated and measured is 180 MHz corresponding to a frequency agility of 3.6%. The bandwidths simulated and measured at -10 dB are 314 and 141 MHz, respectively.

It can be seen from Figure 6 that the return loss simulated achieved -40 dB from 4.5 to 5 GHz and the measured return loss achieved -20 dB from 4.5 to 5 GHz. The

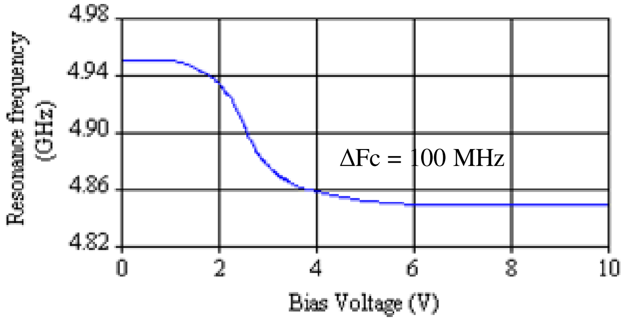

Figure 7. Variation of simulated resonance frequency versus applied DC voltage.

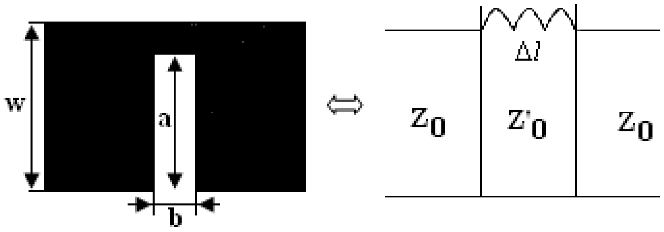

Figure 8. Representation of slot in a printed element and its equivalent circuit.

resonance frequency variation (ΔFr) between the simulated and measured is 250 MHz (5%). The bandwidths simulated and measured at -10 dB are, respectively, 352.56 and 160.25 MHz. This little variation between measurement and simulation data may result from a gap in the precision of the values found for the LC dielectric permittivities.

Figure 7 shows the results of resonance frequency versus bias voltage simulation. It is noticeable that the resonance frequency remains fairly constant for an applied electric field of 6 V, and 80% of the agility is obtained for a 5-V field amplitude.

NEW REDUCED SLOTS PATCH ANTENNA

The second structure has been conceived and affected in order to reduce the size antenna. This has been currently done through slots insertion (Martin et al., 2005). Here, we inserted slots in the printed element. Because of technological difficulties related to the foam substrate, we limited our antenna design to 7 slots. Figure 8 shows the equivalent circuit inductance, Δl, given by the following formula:

$$\Delta l = \frac{\mu_0.\pi.h}{2} \times \left(1 - \frac{Z_0}{Z'_0} \times \sqrt{\frac{\varepsilon_{reff}}{\varepsilon'_{reff}}}\right) \tag{3}$$

where Z_0 is the characteristic impedance of the line of width w, Z_0' is the characteristic impedance of the line of width w-a, h is the substrate thickness, and ε_{reff} , ε'_{reff} are the effective dielectric permittivities of lines of w and w-a widths.

Figures 9 and 10 shows the new design reduced patch antennas that we conceived by HFSS software and the antenna dimensions based on LC. The LC height is kept to 500 µm to allow comparison with the first antenna studied.

Figure 11 shows the simulated return losses for two different permittivities. It can be seen that the return loss achieved -30 dB from 5 to 5.5 GHz. The resonance frequency variation (ΔFr) is 100 MHz, corresponding to a frequency agility of 2%.

Figures 12 and 13 depict the results of simulated and measured return losses with and without applied DC voltage. It can be seen from Figure 12 that the simulated return loss achieved -35 dB from 5 to 5.5 GHz and the measured return loss achieved -5 dB from 5 to 5.5 GHz. The resonance frequency variation (ΔFr) between simulated and measured is 235 MHz corresponding to a frequency agility of 4.7%.

It can be seen from Figure 13 that the return loss simulated achieved -35 dB from 4.5 to 5 GHz and the measured return loss achieved -15 dB from 5 to 5.5 GHz. The resonance frequency variation (ΔFr) between the simulated and measured is 133 MHz (2.66 %).

Figures 14 depict a resonance frequency centered at 5 GHz as expected, and a threshold voltage of approximately 2 V (LC command voltage). It also evidences that a voltage of about 5 V produces 80% agility.

We noticed that for a DC voltage applied, the simulation resonance frequency is decreased of a value of 89 MHz in relation to the result without DC voltage.

The change in second structure (from 20.7 × 21 to 13 × 14 mm rectangular patch) while adding the insertion slots, leads to modified results, in Figures 5 and 6, the stimulated curves are in right hand of measured curves but in Figures 12 and 13, the stimulated curves are in left hand of measured curves.

CONCLUSION

Two structures based on foam substrate and the liquid crystals were designed and simulated. Resonance frequency variation confirmed the frequency adjustment capability of LC-based devices; the extent of adjustment depends on LC anisotropy. In the first and second design, the simulation reflection return losses has been greatly improved by about 10 dB respectively 2.14 dB, along with the variation of the simulation resonance frequency of 100 MHz respectively 89 MHz, both before and after applying a continuous voltage. The accuracy of simulation was verified by comparison with experimental

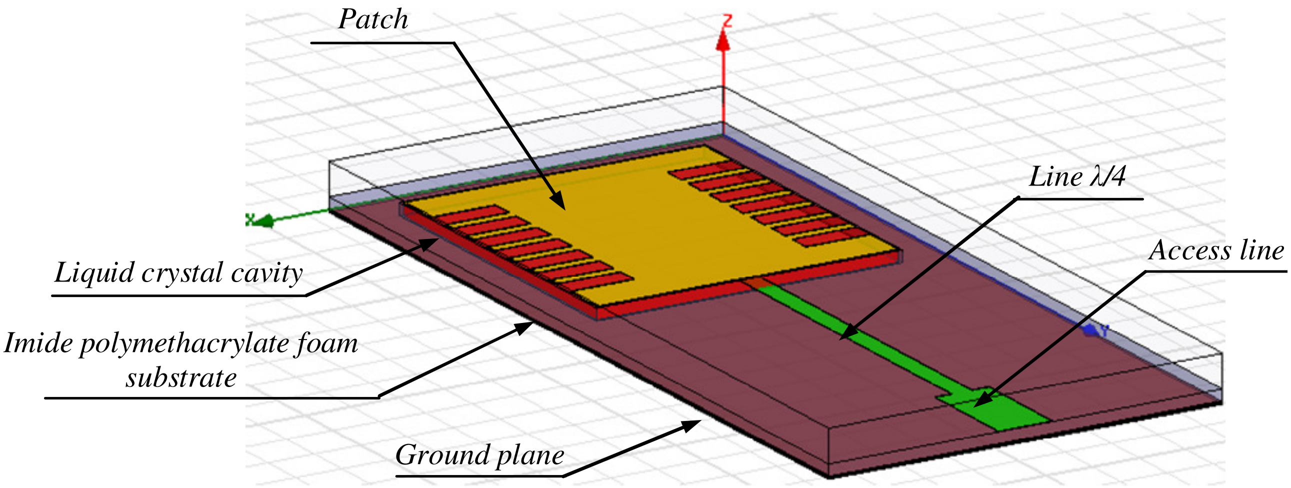

Figure 9. New design slots patch antenna by (HFSS).

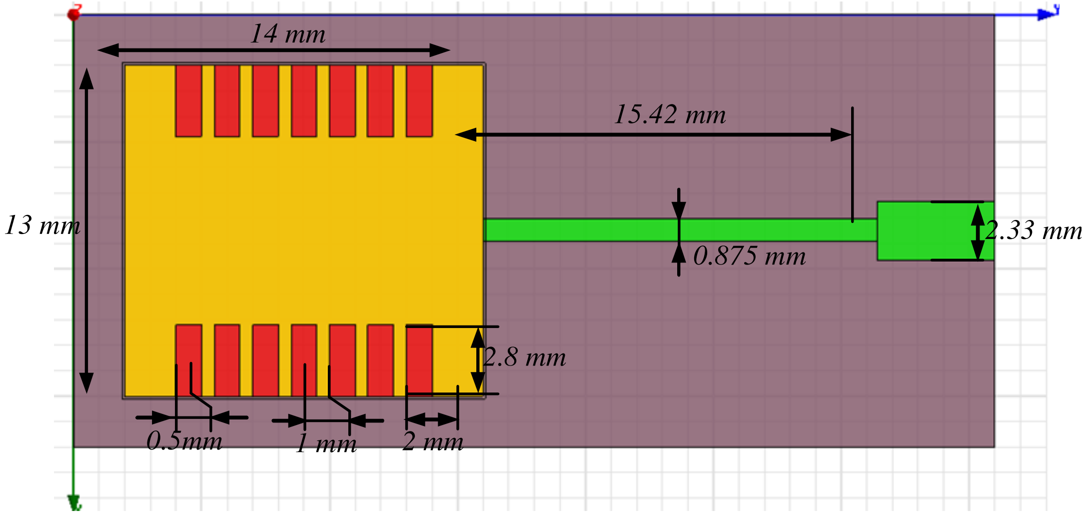

Figure 10. New structure reduced patch antenna dimensions.

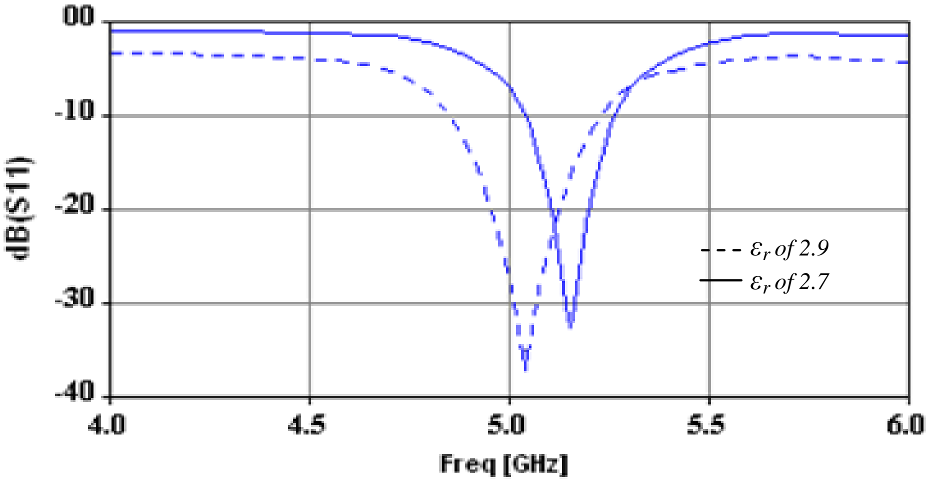

Figure 11. Simulated return losses for two different permittivities.

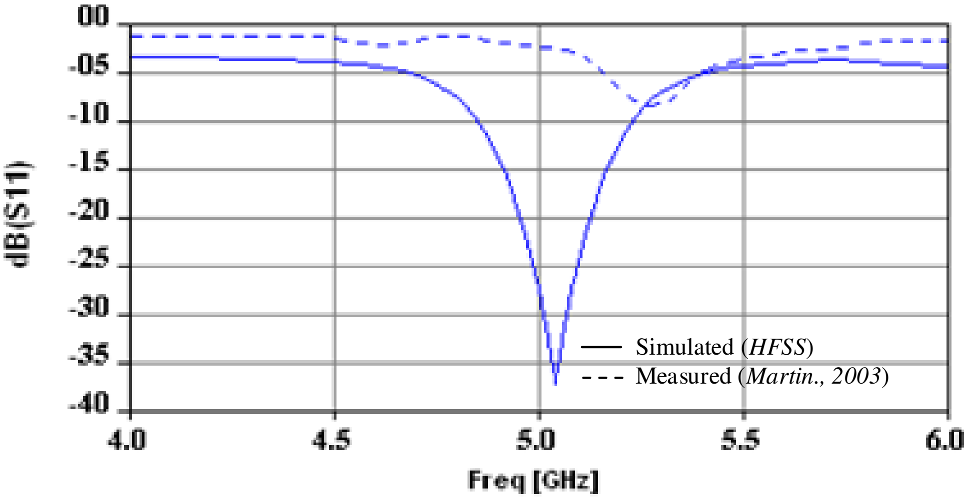

Figure 12. Simulated and measured return losses without applied DC voltage.

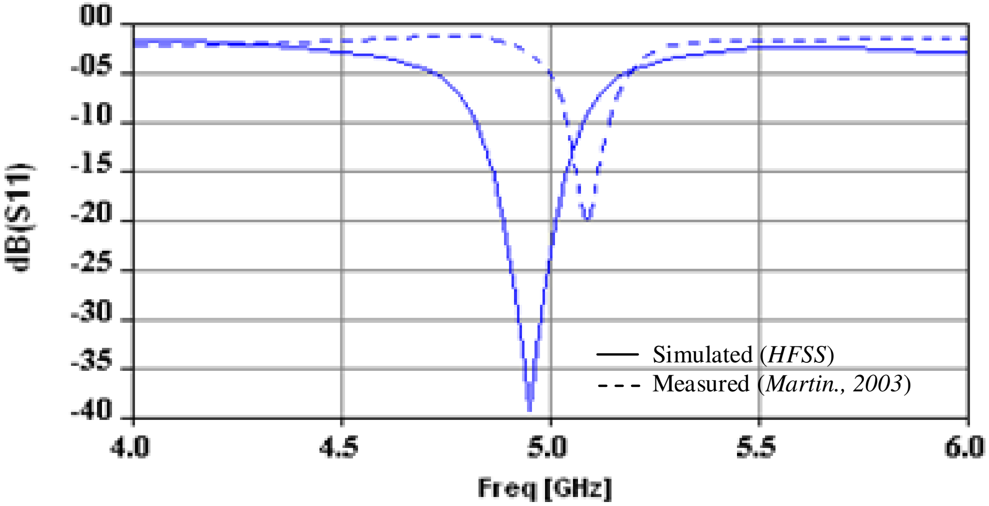

Figure 13. Simulated and measured return losses with applied 20 V DC voltage.

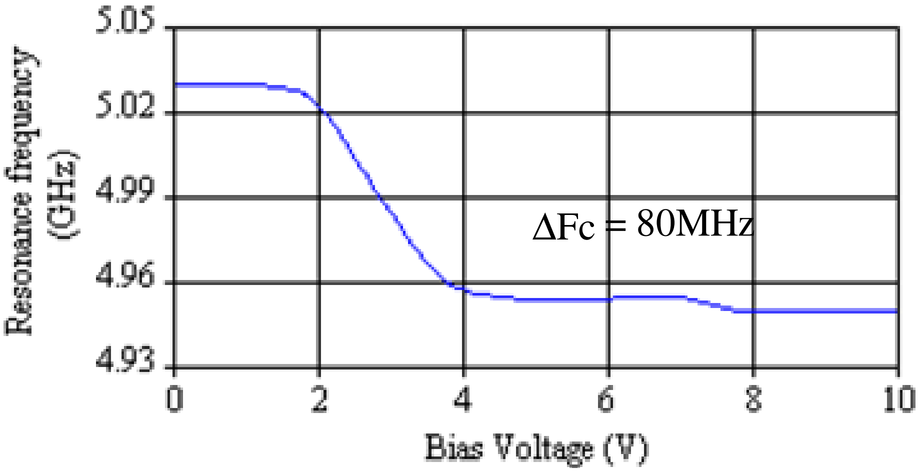

Figure 14. Variation of simulated resonance frequency versus applied DC voltage.

data. The observation of the variation results confirms the potential frequency agility of the devices that use LCs.

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