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Electro-optical anisotropy of liquid crystal for symmetric stub phase-shifter

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In this paper, the design and experimental characterization of a tunable symmetric stub phase shifter in planar technology on electro-optical anisotropy liquid crystal are presented. A reshaped symmetric stub phase shifter structure with a liquid crystal cavity has been used in order to improve the device performance, miniaturization and increase phase of microwave. The proposed design is based on the combination of dielectric symmetric stub and nematic liquid crystals layer. Based on the simulation results, optimization of the geometries are curial for varying the phase of transmitted signal. To benefit from liquid crystal anisotropy and thus obtain agility, a bias voltage is applied. The simulated results of a symmetric stub phase-shifter are compared with measured data, and good agreement is obtained.

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1. Introduction

Due to the increasing demand of the radar applications and wireless communications, enormous efforts have been deployed to bring down the size and cost of microwave circuits. Microwave phase shifters are one of the key components for future reconfigurable radio frequencies (RF) devices, particularly for antenna arrays [1, 2, 3] and microwave filters. The device is concepted and fabricated in a fashion similar to liquid crystal displays which makes fabrication very simple. Also, liquid crystal can give very promising opportunity to realize tunable RF devices. The liquid crystal material consists of anisotropic molecules, where by applying an external electrical field. Simulations and measured of the phase shift and loss of the wave as a function of control voltage applied to the liquid crystal cavity were used. Several approaches have been proposed to study the microwave symmetric stub phase shifters [4, 5, 6].

Thermotropic liquid crystals (LCs) have triggered enormous research interest, since they are promising materials applied in thin-film optic displays, microfluidic sensors, and lubricants [7]. However, the consequence of using highly conjugated compounds to improve electro-optic properties is that the nematic phase is exhibited at high temperatures, over 100°C, and therefore single compounds cannot be used for device applications. The physical properties of LCs, particularly elasticity and viscosity, are crucial to determine their dynamical response to external electric field, flow field, or magnetic field. The application of an electric field results in an orientation of the nematic director either parallel or perpendicular to the field, depending on the sign of the dielectric anisotropy of the nematic medium. Those properties are essentially due to the orientational order of the LC phase, and the knowledge of the orientational order is then important to get good agility [8, 9, 10]. Well known for their optical properties [11, 12], their use in electromagnetic devices has been rare until now. Nevertheless, recent studies [1, 13, 14, 15] have shown their dielectric optical anisotropy property.

This work represents new numerical finite element method (FEM) calculations of the transmission signal and phase of the symmetric stub phase shifter. It is observed from the analysis that designed phase shifter has some limitation such as mechanical variation.

2. Nematic LC properties in the microwave range

In order to describe the operating mode of the agile tunable phase shifter, the microwave properties of the LCs are presented. The main property of the LC in the microwave range is the dielectric anisotropy due to the application of a static electric or magnetic field. All further explanations are related to nematic LCs, which have so far shown the best dielectric properties at microwave and mm-wave frequencies [16].

LCs are specified by different phases depending on their temperature. These phases determine the state of the material, which can vary from a solid state to a liquid state. In this study, LCs are used in the nematic phase, where the molecules float around as in the liquid phase but are still ordered in their orientation. The nematic phase [12-17] is of great interest because of the dielectric anisotropy that permits the frequency agility [18].

Optical anisotropy is then defined as the difference between parallel and perpendicular permittivities and ensues from the following relation:

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

Where $\varepsilon_{//}$ and $\varepsilon_{\perp}$ are, respectively, the parallel and perpendicular relative dielectric permittivity where the dielectric permittivity ε of a material is defined as the ratio of the capacitance C_{mat} of the parallel plate capacitor that contains the material to the capacitance C_{vac}, of the same capacitor that contains a vacuum:

$$\frac{C_{mat}}{C_{vac}} = \varepsilon$$

The dielectric constants are dependent on the temperature and the frequency of the applied field up to the transition to the isotropic liquid.

Fig. 1(a) shows the orientation of the molecules, the least ordered phase is the nematic which has only long-range orientational order (ie: no positional order). In this case, the long axes of the molecules point on the average in the same direction, which is defined by a unit vector commonly known as "the director" (n). Fig. 1(b) shows the optical micrograph of the characteristic Schlieren texture.

Figs. 2 and 3 have shown the chemical structure and the molecular arrangements of 5CB liquid crystal in different phase states. The director vector $\vec{n}$ has the same direction as the nematic LC molecules. A parallel permittivity $\varepsilon_{//}$ of the molecules occurs for a microwave field parallel to the director $\vec{n}$, whereas a perpendicular permittivity $\varepsilon_{\perp}$ is effective for a microwave field perpendicular to the director $\vec{n}$. The result of applying a sufficiently large control voltage to LC is to align the LC along the electric field due to the control voltage. This LC alignment is nearly parallel to the microwave electric field because the transmission mode of the Microstrip line is quasi-TEM. On the other hand, if the control voltage is removed (changed to 0 V), the LC becomes aligned in the direction determined by the alignment layers, which is perpendicular to the microwave electric field.

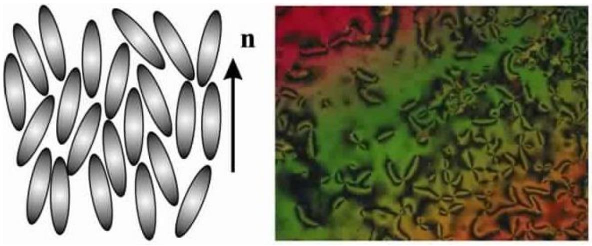

Fig. 1. Nematic phase: (a) an illustration of the orientation of the molecules, and (b) an optical micrograph of the characteristic Schlieren texture

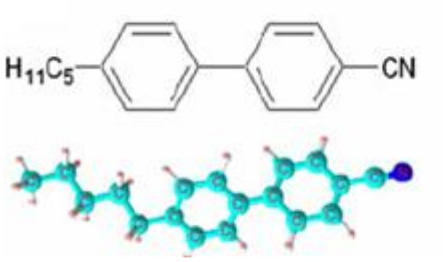

Fig. 2. Chemical structure of nematic liquid crystal 5CB

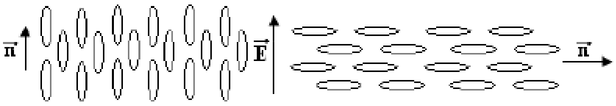

Fig. 3. Configuration matching the permittivity $\varepsilon_{//}$ and $\varepsilon_{\perp}$

3. Phase variation assessment of a tunable phase Shifter

Consider the case of a microstrip line with a dielectric substrate completely metalized on one side and covered with a metallic layer on the other side. The obtained input/output phase shift is set at a given frequency. This phase shift depends on the relative permittivity and the line length, as shown by the following equation:

$$\Phi = \beta.L = \frac{2\pi}{\lambda_g}.L = \frac{2\pi}{\lambda_0}.L\sqrt{\varepsilon} = \frac{2\pi f}{c_0}L\sqrt{\varepsilon}$$

Where;

Φ is the phase in degrees,

L is the length of the active line,

β is the phase constant

$\lambda_g = \lambda_0 / \sqrt{\varepsilon}$ is the guided wavelength,

ε is the relative permittivity of the structure,

f is the frequency and

c_0 is the light speed.

The maximum differential phase shift of a dielectric LC phase shifter can be written as:

$$\Delta\Phi = \frac{2\pi f}{c_0}L(\sqrt{\varepsilon(E)} - \sqrt{\varepsilon(0)})$$

Where $\Delta\Phi$ is the phase difference in degrees, and $\varepsilon(E)$ and $\varepsilon(0)$ represent the relative dielectric permittivity, respectively, with and without an applied field.

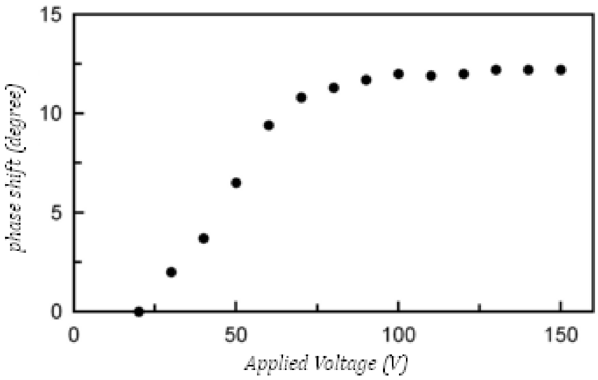

Fig. 4. Voltage dependence of phase-shift in microstrip type device

The magnitude of the orientation is depending on the field strength. Due to the anisotropy of the molecules, this effect can be employed to tune the effective permittivity of the liquid crystal layer inside the devices continuously [19].

Fig. 4 shows the applied voltage dependence of the phase-shift [20]. The phase shift increased with the voltage and was saturated above 100 V. This result indicates that the phase-shift can be controlled by the application external voltage. The phase shift response with and without the application of stepwise voltage was measured.

4. Study and design of a symmetric stub phase-Shifter with the insertion of LC

Phase Shifter has been made in view of reducing the length of the active part and enhancing the interaction between the wave and the matter. In this study, liquid crystals layer can be used as a substrate to the considered dielectric symmetric stub to obtain an electrical tunable phase shifter as shown in Fig. 5. The liquid crystals consists of anisotropic molecules. The rod-shaped molecules tend to align themselves along the surface.

Phase shifter structures are based on transmission lines which are categorized into three types, rectilinear transmission line, continuously varying transmission lines and symmetric stub line.

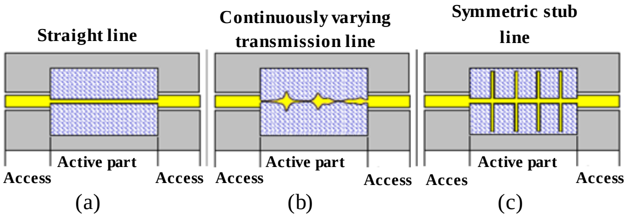

Fig. 5. Phase shifter topology based on LC

The first designed device (Fig. 5(a)) contained a rectilinear transmission line [21] and a cell with a 30-mmlong active part. A second structure (Fig. 5(b)) always in planar technology is based on a technique of continuously varying transmission lines [19] and a cell with a 24-mm-long active part. Then, to increase the phase shift and reduce the device size, a new structure was considered that was still based on an symmetric stub. Fig. 5(c) shows the third design stubs line [22] with an 11-mm-long active part.

For our study, we are interested in the symmetric stub line which shows a reduction in size of 36% with respect to the straight line and with a phase increase.

Fig. 6 shows the design of the symmetric stub phase-shifter based on an LC. The lower part results from the engraved lines on a PTFE substrate of a low relative permittivity. Due to the low relative permittivity of PTFE, the electric field lines are less concentrated than in an LC. The structure optimization allows one to take into account the changes in the LC behavior. The upper part is a brass-made micro-machined cavity used for confining the LC over a coplanar line made on the PTFE substrate. A suitable control voltage of about 10 V is applied in order to obtain the desired tilt of the nematic LC molecules. Thus, the LC relative permittivity variation entails a phase and bandwidth shift as well as the generation of agility.

The phase shifter is needed as a key component in phased-array agile antennas. This component is preferable when the return loss is minimal.

The measurement results are obtained from a vector network analyzer depending directly on the electromagnetic properties of the liquid crystals material. This system consists of exciting the DUT (Device Under Test) by its accesses using a sinusoidal signal of constant amplitude and variable frequency. The simulation was carried out using HFSS software that calculates electromagnetic fields in the frequency domain by locally solving the Maxwell equations.

Figs. 7 and 8 depict the results of simulated and measured return losses with and without applied DC voltage. It can be seen that the return loss achieved −25 dB from 20 to 22 GHz. The resonance frequency variation (ΔFr) between simulated and measured is 500 MHz. The bandwidths simulated and measured at −20 dB are 463 MHz and 330 MHz, respectively. It can be seen from Fig.8 that the return loss achieved −40 dB from 20 to 22 GHz. The resonance frequency variation (ΔFr) between the simulated and measured is 317 MHz. The bandwidths simulated and measured at −20 dB are, respectively, 836 MHz and 600 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.

Fig. 9 illustrates the phase-shift variation versus the applied DC voltage at 20 GHz for the symmetric stub phase-shifter with an LC cavity. The greatest phase shift is obtained for an applied 10 V DC voltage; then LC is supposed to be saturated. The simulated and measured slope average, respectively, are 3°/GHz/cm and 2.77°/GHz/cm, and 80% of the agility is obtained for a 6-V field amplitude. Good agreement is observed in the two plots.

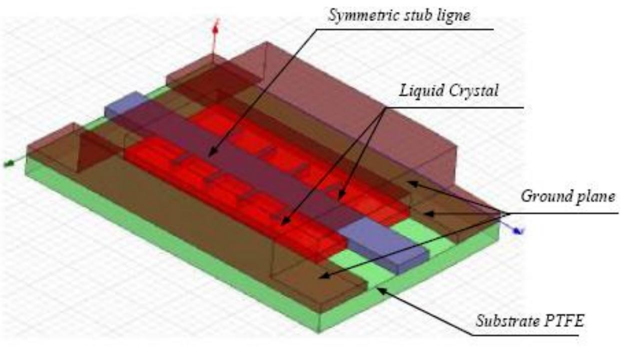

Fig. 6. Structure of a symmetric stub phase shifter with an LC cavity

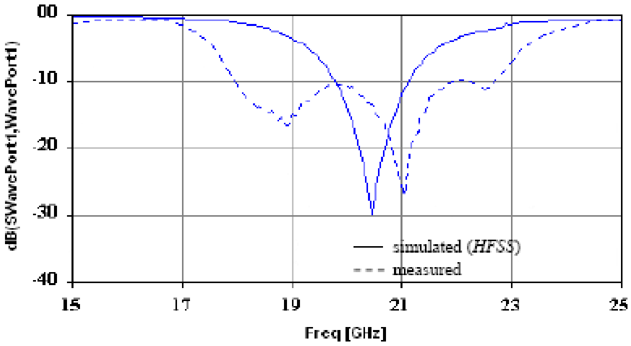

Fig. 7. Simulated and measured return losses without applied DC voltage

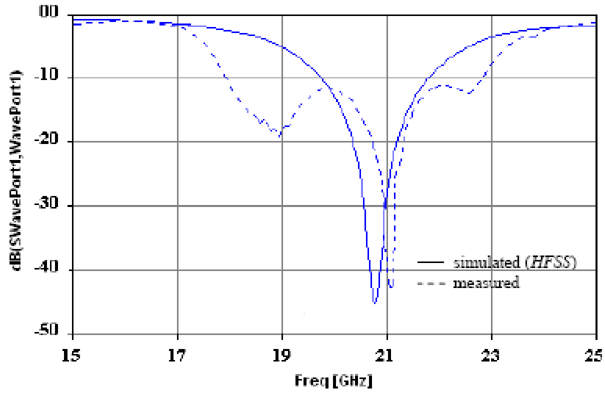

Fig. 8. Simulated and measured return loss with applied DC voltage

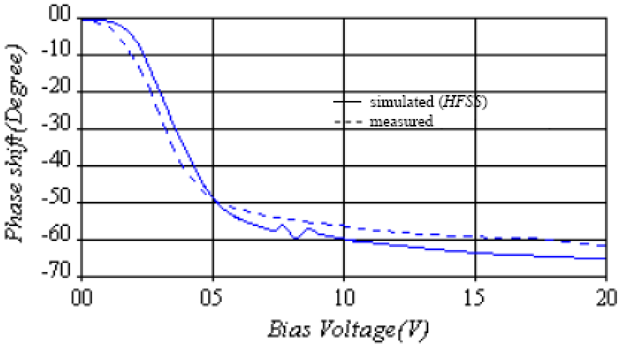

Fig. 9. Simulated and measured Phase shift versus DC voltage at 20 GHz

5. Conclusion

This paper presents the fundamentals of LC material and its applications for reconfigurable phase shifter. Tunable device stub phase shifter with an optical anisotropy LC cavity was designed, simulated and measured. The results shown a simulation slope average 3°/GHz/cm, and 80% of the agility is obtained for a 6-V field amplitude. The reflection return loss has been greatly improved by about 15 dB, along with the variation of the simulation resonance frequency of 310 MHz, both before and after applying a continuous voltage with a bandwidth of 373 MHz. The accuracy of simulation was verified by comparison with experimental data. The observation of the phase deviation confirms the potential frequency agility of the devices that use optical anisotropy of LCs.

This article proposes devices using planar technology based on LC materials. This choice allows the LC anisotropy property to be controlled by an electric field. Numerical results for the symmetric stub phase shifter with an LC cavity are compared with the existing data to confirm the accuracy of the proposed analysis.

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