In-House Made Inverted Microstrip Line Phase Shifter Based on Nematic Liquid Crystal

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***Abstract*—Nematic liquid crystals are anisotropic dielectrics whose properties could be controlled by surface anchoring, external electric or magnetic fields. A typical design method of tunable inverted microstrip line phase shifter based on liquid crystal for microwave application is investigated. Two phase shifter designs based on the proposed method were introduced with the center operation frequency of 10 GHz and 20 GHz respectively. The prototype design operating at 20GHz is manufactured. The dielectric anisotropy of the liquid crystal used for the prototype is 0.45. A differential phase shift of 27.2° was achieved at 20 GHz with the physical length of 20 mm, connected to two coplanar waveguide ports of 50 ohms through vias, and under an external bias of 7 V.**

***Index Terms*—phase shifter, liquid crystal, microstrip line**

I. INTRODUCTION

The state of Liquid Crystals(LC) can be changed depending on temperature and pressure. Molecules of liquid crystals may exhibit a discotic shape or a calamitic shape in which the later one is more useful for tunable devices. The phase of liquid crystals depends on temperature which is named thermometric LC [1], its phase is shaped by the melting temperature point, T_m, and the higher clearing temperature point, T_c, either below or above these two temperatures is outside the discussion in this work, as the so called nematic LC presents unique features such as orientational order when the temperature is between T_m and T_c. The nematic LC phase is characterized by molecules that have no positional order but tend to point in the same direction (along the director) [2].

The intermediate state of the LC between crystalline solids and isotropic fluids is of great importance in various applications and it has drawn a lot of attentions in the past four decades. The anisotropic properties involve definable anisotropic mechanical, optical, and electrical features making LCs suitable for a wide range of potential uses, of which the best known one is LC display. Nematic LC materials possess a birefringence that extends into the microwave range, in recent years, microwave liquid crystal technology emerges as a strong candidate for tunable components in the radio frequency(RF) domain [3]. In spite of a lot of progress has been made on modeling and computation for optical purposes [4], however the conventional methods used for optical characterization are not practical for millimeter or terahertz (THz) wave frequency due to the increased cell thickness. The interaction between the LC permittivity and external microwave fields is not examined in depth as their optical counterparts [5] [6] [7]. In particular, the conventional Indium Tin Oxide (ITO) conductive layers used in optical devices are replaced with copper in microwave devices. This change may cause potential issues in the interface between the conductive layer and the layer for alignment.

In the nematic phase, the average axial direction of rod-like LC molecules can be described by the director, $\vec{n}$, whose orientation is along the long axis of the rod shape. The anisotropy tensor of LC exhibits various permittivities between $\varepsilon_{\parallel}$ in the director direction and $\varepsilon_{\perp}$ in the orthogonal direction to it. The initial alignment of the LC molecules is usually achieved by coating the boundary surfaces of the container for LC with a thin layer of polyimide (PI) film and mechanically rubbing it after curing [8]. The rubbing produces grooves on the polyimide surfaces and they serve like canals to direct the alignment of the LC molecules in the unbiased state. In this paper, liquid crystal based phase shifter designs at microwave and millimeter-wave frequencies are investigated.

II. PHASE SHIFTER DESIGN

The phase shifter consists of three layers as illustrated in Fig. 1. The top layer is the inverted microstrip line, the two ends of the microstrip line are connected with coplanar waveguides (CPWs) through vias. There is a hole on it for LC injection. A rectangular slot is carved in the board of the second layer to form a cavity sealed by the top and bottom layers to contain liquid crystal. The bottom layer is the ground plane. A thin layer of polyimide was coated on the bottom side of substrate 1 and the top side of the ground plane. The dimension of the phase shifter design is indicated in Fig. 2, and the optimized designs at 10GHz and 20GHz are listed in TABLE. I. An external alternating current (AC) source can be used to control the bias voltage on the microstrip line. Bias point shown in Fig. 2 is where the AC was applied. For the 20 GHz design, the differential phase shift is 42.93° while the

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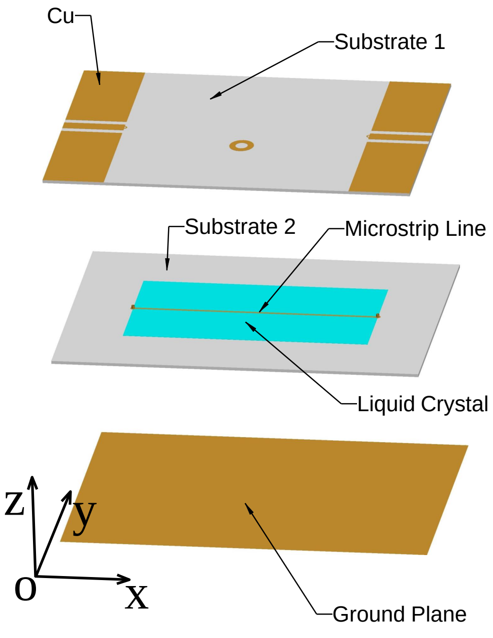

Figure 1. The inverted microstrip line (IMSL) phase shifter design: the top layer is the inverted microstrip line; the middle layer is to provide cavity for the LC material; the bottom layer is the ground plane.

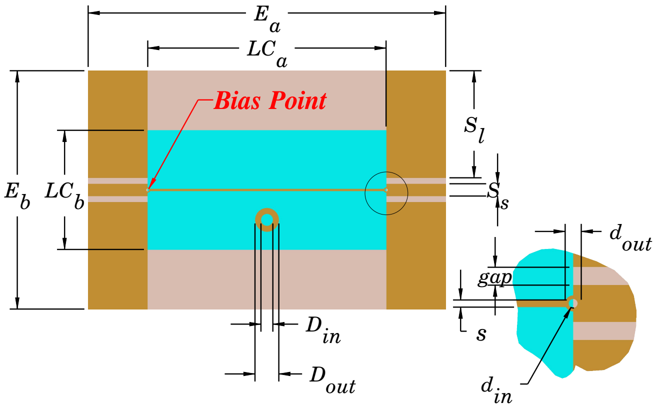

Figure 2. The inverted microstrip line using liquid crystal as substrate and the CPW connections.

relative dielectric constant of the liquid crystal varies from 2.53 to 2.98. The differential phase shift of 34.78° could be achieved for the 10 GHz design, the performance for both designs are shown in Fig. 3.

III. Device Fabrication

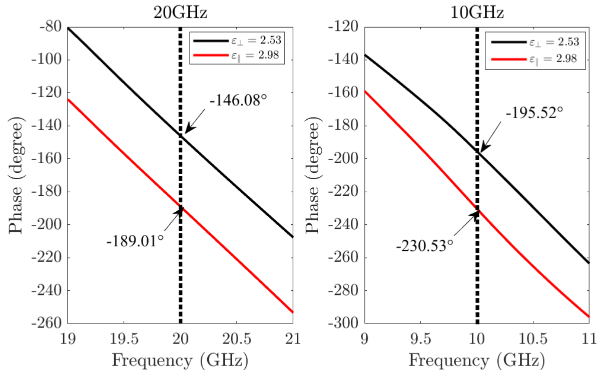

Figure 3. Simulated differential phase shift for the 10 GHz and 20 GHz phase shifter designs.

TABLE I
Phase shifter designs at 20GHz and 10GHz

parameter	values at 20 GHz(mm)	values at 10 GHz(mm)
E_a	30	28.1
E_b	20	22
LC_a	20	18.1
LC_b	10	12
S_l	8.985	8.25
S_s	1.03	1.1
s	0.2	2
D_{in}	1	1
D_{out}	2	2
d_{in}	0.25	0.25
d_{out}	0.45	0.45
gap	0.5	2.2

LC of JC-M-LC-E7 is used in the experiment, with $\varepsilon_{\|} = 2.98$, $\varepsilon_{\perp} = 2.53$, and the dielectric anisotropy of $\Delta_{\varepsilon} = 0.45$. The substrate used for the top and middle layers is RO4350B with a thickness of 0.254mm, the dielectric permittivity (ε_r) of 3.66. The ground plane is made of a copper sheet with a thickness of 1 mm. First the boards for microstrip line and cavity are manufactured. Before assembling, one side of ground plate and the board on the microstrip line side are processed in the following steps: component cleaning, spinning coating, curing, and rubbing. The key steps are cleaning, coating and rubbing. The boards are then baked and unidirectionally rubbed along the short edge direction to provide homogeneous (planar) alignment of the nematic liquid crystal (NLC). By these steps, on the polyimide film surface micro grooves will be created, which leads to a pre-alignment of LC molecules. The polyimide layers also prevent ions from entering the thin NLC layer when an external field is applied.

IV. Results and Discussion

A. Results

The phase shifter device operating at 20 GHz was fabricated. Its S-parameter characteritics were studied by conducting two-port measurements on vector network analyzer. Fig. 6 illustrates the simulated and measured S21 at the frequencies from 19 GHz to 21 GHz. Both of them are more than -4dB and less than -1.5dB. The reflection coefficient of the device depicted in Fig. 5, the bandwidth of the phase shifter reaches 5GHz, and the measured S11 is less than -30dB at the resonance frequency. The differential phase shift versus applied AC voltage at 20 GHz is given in Fig. 7. The phase varies from 92.3° to 119.5° with the differential phase shift

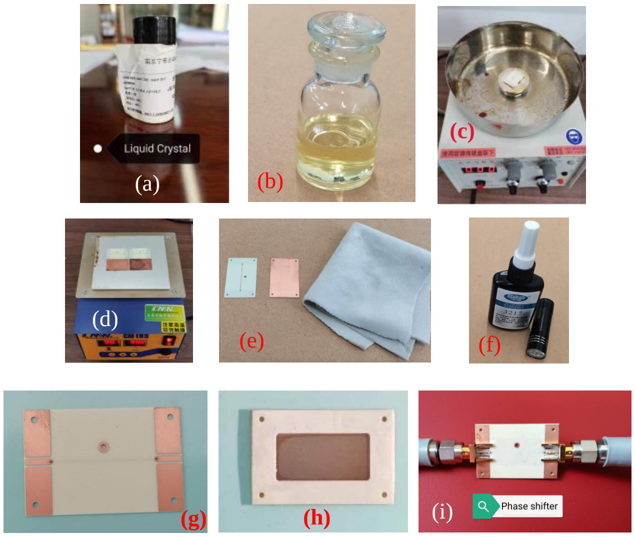

Figure 4. LC manufacturing process, (a) liquid crystal (JC-M-LC-E7) used in this paper, (b) PI, (c) the spinning coating, (d) curing, (e) rubbing, (f) glue, (g)the top layer (h) the liquid crystal cavity, (f)the inverted microstrip line (IMSL) with CPW feed

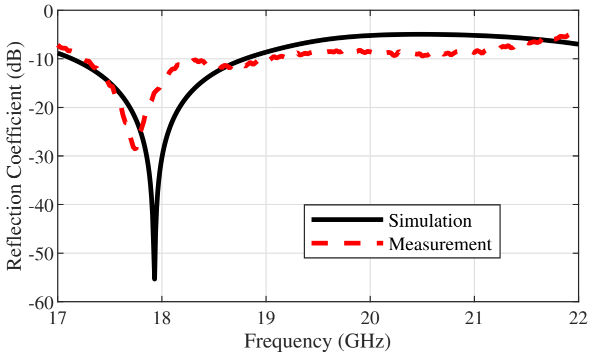

Figure 5. Simulated and measured S11 of LC Phase shifter for 0-V control voltage

up to 27.2° at 20 GHz with the physical length of 20 mm terminated with two coplanar waveguide ports of 50 ohms.

B. Discussion

In simulations, the differential phase shift can reach 42.93° for the 20 GHz design, while it produced only 27.2° in experiment. One reason may be the unverified dielectric anisotropy of liquid crystals, the $\varepsilon_{\|}$ and $\varepsilon_{\perp}$ of JC-M-LC-E7 are 2.98 and 2.53 respectively in the publication. They have not been verified, and they will be measured in the next step, and we only used 7V for safety reason. Another reason could be a technical issue: the thickness of PI and the rubbing process are hard to achieve a high precision.

V. CONCLUSION

A tunable inverted microstrip line phase shifter based on a new liquid crystal has been designed and fabricated. The differential phase shift of 27.2° at 20 GHz is demonstrated with a maximum of 7V bias. The simple design can be improved further to meet the challenges the conventional phase shifters faced: complex circuit, large power consumption and difficulty for miniaturization. The related technologies have a good prospect in millimeter wave and THz applications.

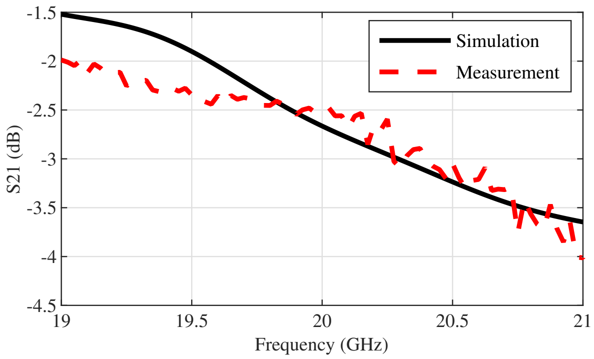

Figure 6. Simulated and measured S21 of LC Phase shifter for 0-V control voltage

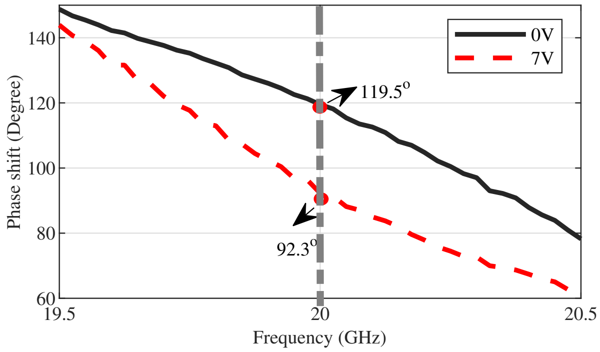

Figure 7. Differential phase shift as a function of applied AC voltage at 20 GHz, the physical length of the LC in the phase shifter is 20mm.

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