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High FoM Liquid Crystal based Microstrip Phase Shifter for Phased Array Antennas

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***Abstract* –An electrically tunable microstrip phase shifter for applications of phased array antennas is designed based on nematic liquid crystal material. The experimental results show a tunable differential phase shift up to 270° at 10 GHz, and the insertion loss is less than 9 dB at 1-10 GHz range. By optimizing both of the liquid crystal tuning efficiency and overall loss, an average figure-of-merit (FoM) $40^{\circ}/dB$ has been achieved in frequencies 1-10 GHz.**

***Index Terms* — Nematic liquid crystal, electrically tunable phase shifter, impedance adaptor, phased array antennas.**

1. Introduction

In recent years the demand for tunable phase shifters operating in frequencies 1-10 GHz has risen constantly, because tunable phase shifters are key components in phased array antennas and other communication systems. There are several ways to achieve tunable phase shifters, such as using ferroelectric materials, microelectromechanical systems (MEMS), and semiconductors [1]-[3]. Recently nematic liquid crystal (NLC) has been attracting much attention as a tunable anisotropy dielectric for high frequency applications. It owns relatively low dielectric loss and acceptable tuned range in microwave (MW) spectrum. Other advantages of low operation power, continuous tuning ability and cost effective fabrication process make NLC more attractive than other tunable materials for MW application. NLC based tunable phase shifters, antennas, capacitors, resonators and filters have been fabricated [4].

In this work, we demonstrate a NLC based tunable phase shifter operating in frequencies 1-10 GHz. The performance of the proposed phase shifter has been improved by optimizing the material selections and device dimensions.

2. Properties of used nematic liquid crystal

A rod-shape NLC molecule is shown in Fig. 1 (a), and it illustrates the anisotropic property of NLC. The parallel permittivity $\varepsilon_{\parallel}$ and perpendicular permittivity $\varepsilon_{\perp}$ are measured along its long and short axis, respectively. Hence any orientation in between will lead to a different effective permittivity between $\varepsilon_{\perp}$ and $\varepsilon_{\parallel}$. The dielectric loss tangent of NLC is anisotropic as well, and it changes between two extreme values $\tan\delta_{\perp}$ and $\tan\delta_{\parallel}$.

The orientation of NLC molecules can be regulated under external electric or magnetic fields, and it results in a tuning of effective permittivity for NLC substrate. Fig. 1 (b)-(d) demonstrate the orientations of NLC molecules under various bias voltages. The long axis of NLC molecules has the trend to align in parallel along the biased electric fields. As can be seen from Fig. 1, alignment layers are used in order to pre-align NLC molecules, and microstrip line (ML) structure and ground plane are used as electrodes to apply bias voltages. When there is no bias voltage, NLC molecules stay at the pre-alignment position, and the effective permittivity of NLC layer is $\varepsilon' \approx \varepsilon_{\perp}$. As the bias voltage increases, NLC molecules tend to rotate towards ML through the combination of pre-aligned elastic force and external electric force. In this case its permittivity is $\varepsilon_{\perp} < \varepsilon' < \varepsilon_{\parallel}$. When the bias voltage reaches its saturated value, the long axis of NLC molecules will be in parallel to the applied electric fields, and the NLC effective permittivity is $\varepsilon' \approx \varepsilon_{\parallel}$.

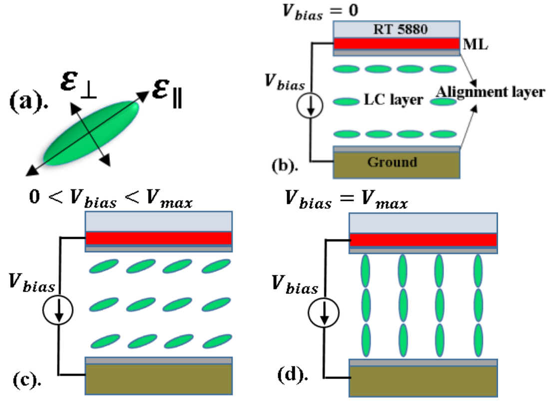

Fig. 1. (a) Single NLC molecule (b)-(d) states of NLC molecules under various bias voltage: $V_{bias} = 0$; $0 < V_{bias} < V_{max}$; $V_{bias} = V_{max}$

NLC material GT3-24002 is used in this study, and its measured properties at 10 GHz and 23 ℃ are as follows: $\varepsilon_{\perp} = 2.5, \varepsilon_{\parallel} = 3.3$, $\tan\delta_{\perp} = 0.0123$, $\tan\delta_{\parallel} = 0.0032$.

3. Phase shifter design and measured results

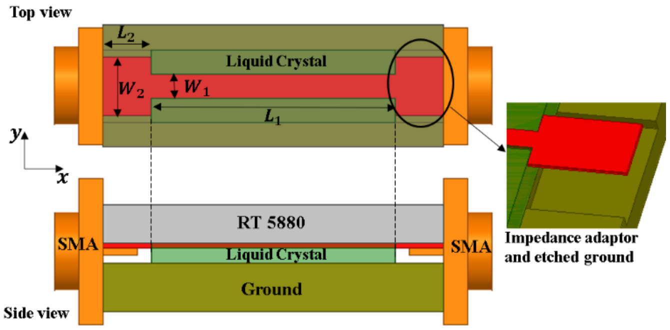

Fig. 2. Configuration of the NLC based phase shfiter

The maximum differential phase shift of a NLC based tunable phase shifter can be written as follows:

$$\Delta\Phi = \Phi_2 - \Phi_1 = \frac{2\pi f L}{c}\left(\sqrt{\varepsilon_{eff,\parallel}} - \sqrt{\varepsilon_{eff,\perp}}\right)$$

Where L is the physical length of phase shifter, f is the operation frequency, c is the speed of light, $\varepsilon_{eff,\perp}$ and $\varepsilon_{eff,\parallel}$ are the effective relative permittivity of NLC substrate for the unbiased and fully biased state, respectively.

The proposed NLC based phase shifter configuration is shown in Fig 2. NLC material is sandwiched between aluminum ground and $0.787\ mm$ thick Rogers RT 5880 with the relative permittivity $\varepsilon_r = 2.2$ and dielectric loss tangent $\tan\delta = 0.0009$. The thickness of ML and NLC substrate are $0.017\ mm$ and $0.113\ mm$, respectively. Because of the liquid-like state of NLC, SMA contact doesn't touch with NLC layer, hence impedance adaptors with width W_2 shown in Fig. 2 are applied to reduce device insertion loss. The ground plate is etched in order to insert SMA contact. The dimensions of the ML structure are as follows: $W_1 = 0.276\ mm$, $W_2 = 5\ mm$, $L_1 = 170\ mm$, $L_2 = 3\ mm$. The device materials and dimensions are selected properly to maintain large NLC tuning efficiency and low insertion loss. For instance, Rogers RT 5880 with low relative permittivity was selected in order to make more MW fields through LC layer and increase NLC tuning efficiency; NLC substrate thickness was increased to $0.113\ mm$ for reducing overall loss while maintain acceptable tuning efficiency. During assembling, the ground plate and RT5880 substrate should be assembled anti-parallel in terms of the rubbing direction of the deposited alignment layer, in which case the LC molecules sandwiched between them can be aligned parallelly and symmetrically.

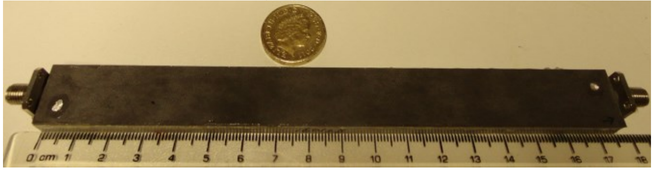

Fig. 3. The photograph of the fabricated phase shifter

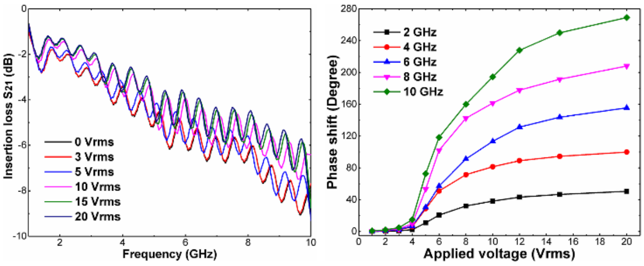

Fig. 4. Measured insertion loss and tuned differential phase shift of the proposed phase shifter

Fig. 3 shows the photograph of the fabricated phase shifter. The insertion loss and tuned differential phase shift of the NLC based phase shifter under various driven voltages are presented in Fig. 4. The maximum insertion loss is less than 9 dB at 1-10 GHz range. What is more, at 10 GHz the tuned differential phase shift is 270° with 20 Volts external driven voltage. Fig. 5 depicts its figure-of-merit (FoM), which is defined as the ratio of the maximum differential phase shift and the insertion loss associated with the maximum phase shift. It is clear to see that the measured insertion loss and FoM have variations and ripples, which are mainly caused by the fabrication error because of the non-uniform NLC layer. The average FoM during the whole frequency range is $\sim 40^{\circ}/dB$, which is larger than that in reference [5], [6].

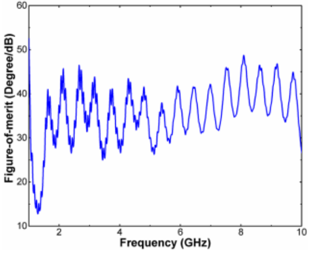

Fig. 5. Measured FoM of the proposed phase shifter

4. Conclusion

We have demonstrated a nematic liquid crystal based electrically tunable microstrip phase shifter with high performance. The fabricated device possesses a tunable differential phase shift up to 270° at 10 GHz, and the insertion loss is lower than 9 dB at frequencies 1-10 GHz. It is suitable for applications of phased array antennas.

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