Low-loss tunable dielectrics for millimeter-wave phase shifter: from material modelling to device prototyping

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Abstract. Passively controllable millimeter-wave phase shifters based on continuously tunable dielectrics offer promising alternatives to conventional switch-based topologies (e.g. active semiconductor devices and MEMS) with digital resolution. However, only a handful of tunable dielectrics have thus far been identified with high tunability and low loss, among them, liquid crystal (LC) in the nematic phase is of research and development interest. This work presents the modelling of LC materials at 66 GHz based on a novel shielded coplanar device structure in place of traditional waveguides. Phase shifters of 0-π tunability are fabricated and measured, with an insertion loss of -4 dB and return loss lower than -15 dB demonstrated.

1. Introduction

Liquid crystal (LC) in the nematic phase has been reported extensively in electronically tuned microwave devices (e.g. resonators, filters, antennas, frequency-selective surfaces, and phase shifters) [1] that are key components of a phased antenna array system. Working as a reconfigurable tuning dielectric material based on molecular shape anisotropy [2], LC offers highly attractive properties [3] over competing technologies, e.g. appreciable tunability [4], low polarisation loss (especially above 10 GHz) [5], ease of control (continuous tuning with low power consumptions) [6], transparency, and possible integration with printed and flexible circuit technologies. Specifically, the continuous tunability (i.e. analog functionality) is especially useful in beam-scanning applications with improved beam-pointing accuracy and compensation for temperature (or aging) drifts.

A rod-shaped model of the LC in nematic phase is depicted in Figure 1, with mobile charges inside a rigid core polarised by an external low-frequency bias field (5 Hz for example) as shown in Figure 2, resulting in reoriented dipole moments (66 GHz) and polarisation difference due to shape anisotropy.

Figure 1. Exemplary molecule representation of the nematic LC.
Figure 2. Electronic biasing of LC molecules interacting with 66 GHz signal.

While optical and microwave field interactions with LC have been well researched, there have been significantly fewer studies into the device development combined with LC at the millimeter-wavelength range, except for waveguide-based implementations [7, 8] biased with bulky and power-consuming magnets. Developing LC-based compact planar phase-shifting structures remains an embryonic proof-of-concept stage, i.e. design and optimisation space remains largely unexplored. This work proposes a novel planar device configuration (Figure 3) realised in shielded coplanar waveguide (SCPW) for 66 GHz signal and investigates how to optimally combine the structure with LC as tunable dielectrics for a phase-shifting device. Figure 3 illustrates the 66 GHz electric and magnetic vector fields as exhibited by the proposed SCPW. The wave port (analysed in red) covers the critical elements of the structure, i.e. the core, coplanar ground planes, enclosure, LC-filled cavity and the PTFE substrate. The enclosure-attached structure substantially equalizes the grounding electrodes’ electric potential, and thus allowing a true-TEM mode propagation whilst suppressing parasitic parallel-plate mode, uneven slot line mode, and the associated modes-coupling problems. With all the ground planes physically and electrically bonded, the top metal enclosure also provides mechanical strength and serves as a heat sink for high-power applications. In a summary, this via-free and bond wire-free SCPW topology including an enclosed ground plate provides a low-loss and low-cost device-on-substrate solution for millimeter-wave devices.

Figure 3. Simulated SCPW mode at 66 GHz for the proposed SCPW structure.
2. Investigation of LC material’s tunability with the novel SCPW

2.1. Surface-anchoring alignment direction for maximum tunability

The maximum differential phase shift ($\Delta \Phi_{21}$) is given by (1) below for a tunable transmission line with a length of $L$ at the frequency of $f$. $\varepsilon_{\text{eff}}(\max{\text{bias}})$ and $\varepsilon_{\text{eff}}(\text{ref.bias})$ denote the SCPW’s effective permittivity in the LC’s saturation and reference voltage-biasing states, respectively.

$$
\Delta \Phi_{21} = \frac{2\pi f L}{c_0} \times \left( \sqrt{\varepsilon_{\text{eff}}(\max{\text{bias}})} - \sqrt{\varepsilon_{\text{eff}}(\text{ref.bias})} \right)
$$

Figure 4 below illustrates the LC directors’ orientation (obtained using LCD Master) and the implications on $\varepsilon_{\text{eff}}(\text{ref.bias})$ under two rubbing (surface-anchoring) directions for the alignment layer. The red arrows indicate the electric field direction, whilst the background colours represent the electric field intensity distribution. Based on the nature of a TEM mode (zero cut-off frequency), the millimeter-wave electric vector field is identical in the polarisation with that at low frequencies. To maximise the achievable $\Delta \Phi_{21}$, the reference bias is strategically selected as the voltage below Fredericks transition (e.g. $< 4$ V) and with a longitudinal LC alignment by surface-anchoring the LC directors parallel with the wave-propagation direction as shown in Figure 4 (b).

![Figure 4](image1)

(a) Transversal surface-anchoring:

$$
\varepsilon_{\text{eff}}(\text{ref.bias}) > \varepsilon_{\text{eff,}\perp}.
$$

(b) Longitudinal surface-anchoring:

$$
\varepsilon_{\text{eff}}(\text{ref.bias}) = \varepsilon_{\text{eff,}\perp}.
$$

Figure 4. Effect of surface-anchoring direction on $\varepsilon_{\text{eff}}(\text{ref.bias})$ below Fredericks transition.

Given a longitudinal surface alignment and under the reference bias state (below the Fredericks threshold), the millimeter-wave polarisations are perpendicular to the LC orientations. Therefore, taking $\varepsilon_{\text{eff}} = \varepsilon_{\text{LC,}\perp}$ is rigorous. The employed surface-anchoring direction can also avoid alignment-related defects (e.g. disclination lines). More importantly, the achievable maximum tuning range is the largest as compared with any other surface-anchoring directions. Therefore, we tailor our design based on the longitudinal surface anchoring.

2.2. LC director calculations based on finite element simulations

LCD Master (a finite element solver) is used to perform low-frequency calculations (numerically solving Poisson’s equations) to gain the bias voltage-dependent LC molecular orientations and consequently the spatial (local) LC dielectric constant, which is subsequently fed into electromagnetic simulators for 66 GHz full-wave analysis. Longitudinal rubbing with a pretilt angle of $3^\circ$ and anti-parallel assembling is assumed. The convergence of the director simulation is reached when refining the residual error criteria to be $10^{-6}$ for the saturation biasing states (above 18 V), as evidenced in Figure 5. Accordingly, the $\varepsilon_{\text{eff}}(\text{ref.bias})$ and $\varepsilon_{\text{eff}}(\max{\text{bias}})$ are obtained and detailed in Table 1, i.e.
2.4078 and 2.9725, respectively, based on which the line length is designed to meet the targeted phase shift of $\pi$ in this work with LC thickness of 140 $\mu$m.

![Convergence of LC director](image1)

(a) Convergence of LC director.  

![LC director distribution at 20 V (saturation bias)](image2)

(b) LC director distribution at 20 V (saturation bias).

Figure 5. LCD Master 3D simulations of LC-based SCPW from 0 V to saturation bias.

Table 1. Effective permittivity of GT3-24002 LC in SCPW (simulated at 66 GHz).

| Bias voltage | Dissipation factor | Inherent | Effective |
|--------------|--------------------|----------|-----------|
| 0 V          | 0.0123             | 2.5      | 2.4078    |
| 20 V         | 0.0032             | 3.3      | 2.9725    |

3. Device prototype and experimental validation

A millimeter-wave 0-$\pi$ continuously tunable LC SCPW phase shifter is prototyped based on our well-established experience [4-6, 9] in LC-based devices fabrication, i.e. from electrodes patterning (shown in Figure 6), surface finishing, alignment agent deposition and rubbing, to LC filling, and packaging with glue and connectors.

![Fabricated PCB by photolithography](image3)

(a) Fabricated PCB by photolithography.  

![Enclosure machining by wire erosion](image4)

(b) Enclosure machining by wire erosion.

Figure 6. Images of electrodes patterned and substrates shaping.
Figure 7 shows the measurement setup using a two-port network analyser, with the performance results of S parameters reported in Figure 8. The impact of silver conductive paste (SCP) adding to the grounding path’s electrical connectivity is measured and evaluated for two groups of devices assembled without and with SCP (applied between CPW’s ground planes and the enclosure).

**Figure 7.** Measurement of the fabricated LC-filled SCPW device.

(a) Measured bias voltage response of differential phase shift.

(b) Measured return loss.

(c) Measured insertion loss.

**Figure 8.** Device characterisation of the LC-based SCPW phase shifter prototype.
Looking into the voltage response of the shifted phase, 0-π analog phase shift is achieved by a voltage bias from 0 V to 20 V, with a measured insertion loss of -4 dB at 66 GHz. To be more specific, there is a quasi-linear phase shift versus voltage response range from 5 V (the threshold of Fredericks transition) to 10 V (the start of saturating), wherein the applied low-frequency electric field in the proposed SCPW cavity controls LC’s molecular polarizability to vary continuously and contribute to agility efficiently. The minor nonlinearity in this range is due mainly to the trapped charges in the alignment agent, which distorts the low-frequency field.

Note that the return loss well below -15 dB is achieved across a wideband from 54 GHz to 66 GHz. Albeit pressing the enclosure on the PCB substrate carefully, the non-uniformity due to the uncertainty of the applied SCP layer results in elevated return loss and adds to the insertion loss, which cancels out the benefit of improved conducting paths connecting the grounds.

4. Conclusion

A 66 GHz electronically controllable phase shifter in liquid crystal tunable dielectrics technology is modelled, simulated and experimentally verified. Based on an in-depth understanding of the basic material properties, a novel phase shifting device architecture in SCPW is proposed, and optimised combining with LC to deliver a continuously tunable, low insertion and return losses, moving-parts-free, compact size and cost-competitive hardware solution, which opens the door of low-cost manufacturing for millimeter-wave reconfigurable applications, such as feeding a phased array antenna for use in the inter-satellite links.

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