

Design of A Phase Shifter Based on the Coupled Microstrip Line With Tunable Liquid Crystal

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Abstract—In this letter, a liquid crystal phase shifter is proposed. It is designed using the method of coupled-line bandpass filters. The liquid crystal directly below the coupled lines and microstrip lines can be turned by applying a different voltage. Voltage causes the permittivity of the liquid crystal to change, thus enabling the achievement of phase shifting. Since the proposed phase shifter structure is more complex, it differs from the original microstrip line. This work performed a detailed parametric sweep analysis on the design dimensions. Then, using the determined dimensions, a phase shifter was initially designed, and simulation analyses were conducted. The structure operates with a 20% relative bandwidth at a center frequency of 6.75 GHz, and this design achieves dynamic phase shift control exceeding 65°. The structure has an insertion loss of less than 1.5 dB, and it provides a larger phase shift in the high-frequency region.

Index Terms—Coupled-line, Phase shifter, liquid crystal

I. INTRODUCTION

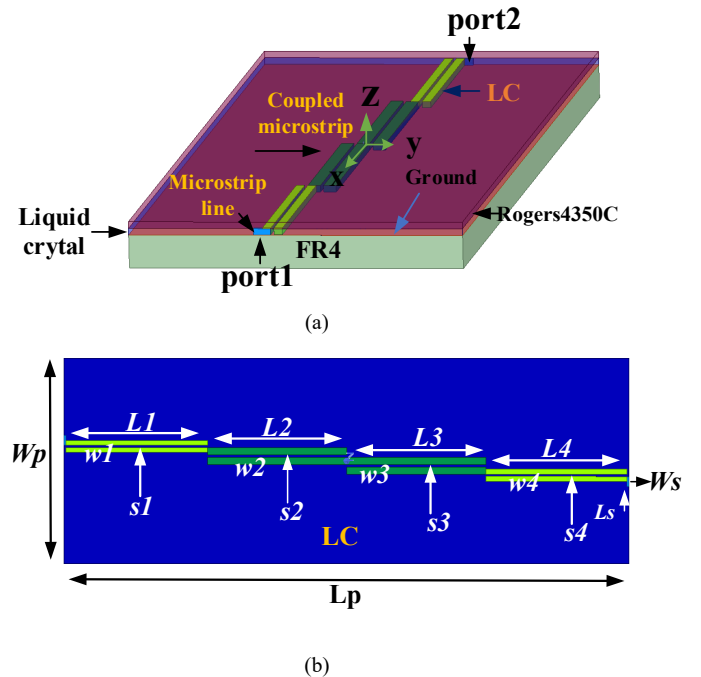
Liquid crystal phase shifters have high integration, a wide phase-tuning range, low power consumption, and compatibility with easy processing. They are widely used in RF, microwave, and terahertz systems. A lot of research efforts focus on improving the performance of phase shifters. For example: the work reported in [1] achieved a 117° phase shift (FOM 30.6°/dB) at 34.3 GHz; the study in [2] realized a 0°–360° phase shift but with a narrow bandwidth; the research in [3] achieved a 360° phase shift across 28–30 GHz with an insertion loss greater than 10 dB; the design in [4] adopted striplines (FOM 66.4°–88.5°/dB, 10–60 GHz) yet suffered from poor integration; the scheme proposed in [5] utilized LC-DGS and delivered better performance; the device developed in [6] was a 270° phase shifter (1–10 GHz) designed for phased arrays. Therefore, Liquid crystal phase shifters have promising prospects. But it currently also faces some issues, such as limited bandwidth, difficulty in integration, and so on.

This paper proposes a design method based on coupled-line band-pass filters to design a liquid crystal-tunable RF phase shifter. Firstly, the phase shifter designed using the design concept of band-pass filters can achieve low insertion loss and a wide frequency band. Secondly, by applying different DC voltage biases to the liquid crystal, its dielectric constant changes, enabling the phase shifter to have the function of voltage-tunable phase shift. Finally, to verify the feasibility of the proposed phase shifter, a third-order coupled-line liquid crystal phase shifter was designed and simulated.

II. MODEL AND PARAMETER SIZE ANALYSIS OF THE LIQUID CRYSTAL SHIFTER

A. Structure Introduction

The geometric model and parameter dimensions of the liquid crystal phase shifter are shown in Fig. 1. The length and the width of the entire model are 28 mm and 12 mm, respectively. It consists of three layers: the top layer is Rogers 4350C, the middle layer is liquid crystal, and the bottom layer is FR4 substrate. The transmission lines are below the Rogers 4350C, and consist of microstrip lines and coupled microstrip lines, respectively. In Fig. 1(a), the blue parts on both sides are microstrip lines. The width (W_s) and length (L_s) of these microstrip lines are 0.5 mm and 0.1 mm, respectively. They lead out the coupled lines to facilitate the addition of waveguide ports for simulation. As shown in Fig. 1(b) and (c), directly below the coupled lines and microstrip lines is a voltage-tunable liquid crystal dielectric layer. This liquid crystal layer has a height of h_2 . Below the liquid crystal layer is a copper foil ground plane. Beneath the ground plane is an FR4 substrate. It serves as structural support. The initial design parameters are summarized in Table 1. This design employs a third-order band-pass filter method, and the model is centrosymmetric.



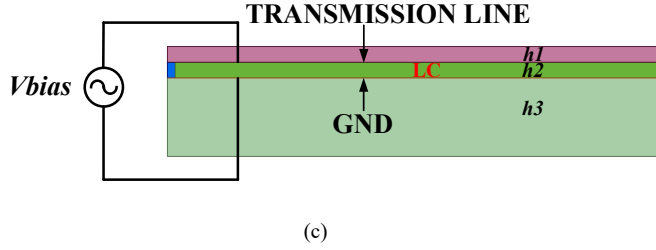


Fig. 1. 3D Model of the Liquid Crystal Phase Shifter. (a) Overall view. (b) Top view. (c) side view.

TABLE I

INITIAL DESIGN DIMENSIONS OF THE PROPOSED SHIFTERS (UNIT: mm)

Parameter	$S1$	$S2$	$L1$	$L2$	$W1$	$W2$	W_s	L_s
Value(mm)	0.1	0.1	6.1	6.2	0.2	0.4	0.5	0.1

As shown in Table 1 above, detailed design parameter sizes are provided. $S1$ and $S2$ are the gaps of the coupled lines, which mainly determine the coupling strength. Due to strong coupling, the sizes are limited by the precision of the processing. $W1$ and $W2$ are the widths of the coupled lines, which can be derived from the even-odd mode analysis of the coupled lines. $L1$ and $L2$ are the lengths of the coupled lines. Additionally, there are unlisted sizes in the table: the thickness of the top Rogers4350C plate $h1$ is 0.5 mm; the thickness of the middle dielectric (liquid crystal) layer $h2$ is 0.2 mm; the bottom FR4 dielectric substrate only plays a supporting role with $h3$ of 1 mm; the length and width of the entire model are Lp of 28 mm and Wp of 12 mm respectively.

B. Parameter Scanning Analysis of $L1$ and $L2$ for the Liquid Crystal Phase Shifter

As shown in Fig. 2, parameter scanning is performed on the lengths of the coupled lines. Due to symmetry, only $L1$ and $L2$ need to be scanned. In the design bandwidth, we aim to find the parameters with a central frequency of 6.75 GHz. Firstly, parameter scanning is conducted on $L1$ and $L2$. The scanning is performed sequentially. As shown in Fig. 2(b), when $L1 = 6.5$ mm and $L2 = 6.4$ mm, the central resonance point is near 6.75 GHz, which corresponds to the initially designed target central frequency. Therefore, $L1 = 6.5$ mm and $L2 = 6.4$ mm are parameters that meet the design requirements. During this process, the relative permittivity of liquid crystal LC2 is still set to 2.9.

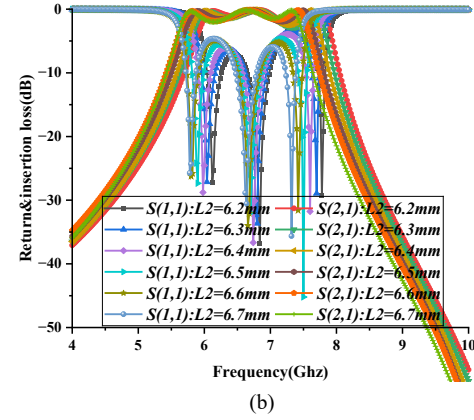
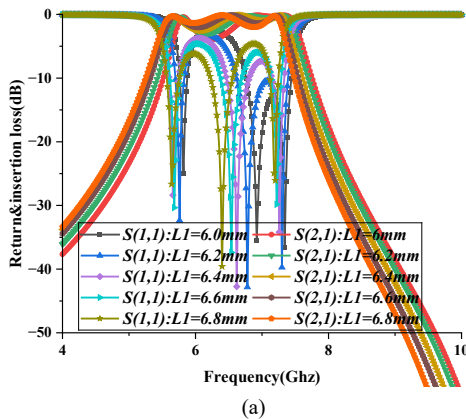
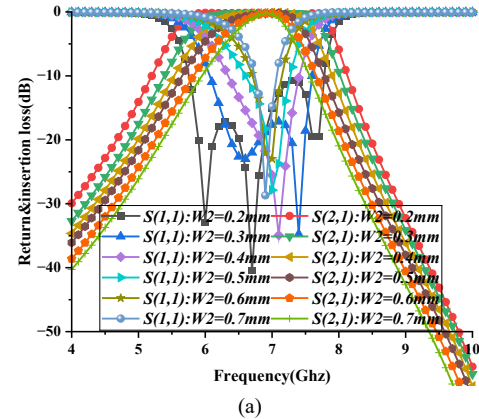


Fig. 2. The Parameter Scanning Analysis of $L1$ and $L2$. (a) When $L2 = 6.8$ mm, with different dimensions of $L1$, scans were conducted on the insertion loss $S(1,1)$ and return loss $S(2,1)$ of the phase shifter. (b) When $L1 = 6.5$ mm, with different dimensions of $L2$, scans were conducted on the insertion loss $S(1,1)$ and return loss $S(2,1)$ of the phase shifter.

C. Parameter Scanning Analysis of $W1$, $W2$, and W_s for the Liquid Crystal Phase Shifter

As shown in Fig. 3, to balance port matching under different permittivities and reduce insertion loss, we firstly performed parameter simulations on a short section of microstrip line. The length of this microstrip line (L_s) is set to 0.1mm, and the width (W_s) is 0.45mm. The device is designed with a liquid crystal having a permittivity $\epsilon_r = 2.9$. It is the median of the variation range, and it accounts for changes in the voltage applied to the liquid crystal.

Furthermore, parameter scanning was conducted on the width of the coupled microstrip line. As shown in Fig. 3(a), with an increase in parameter $W2$, it can be observed that the width W of the coupled line affects the bandwidth. Moreover, since the width W of the coupled line determines the mutual capacitance and self-capacitance of the coupled line under even-odd mode excitation, it also affects the coupling strength to some extent. In Fig. 3(a), a complementary relationship is evident between bandwidth and resonance point. Such a relationship also exists in Fig. 3(b), but it is not as obvious as that in Fig. 3(a). When selecting the design dimensions of the phase shifter, we can make choices based on different requirements for bandwidth.



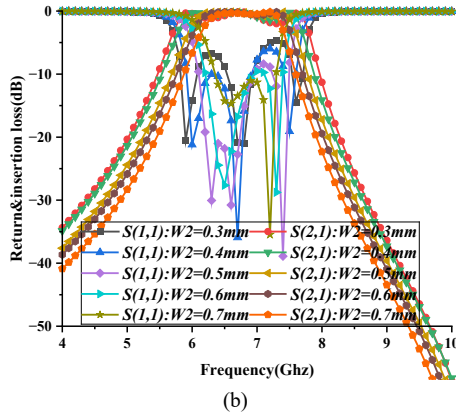


Fig. 3. The Parameter Scanning Analysis of W1 and W2.(a) W1 = 0.1 mm, with a parametric sweep on the dimension of W2: the insertion loss and return loss of the proposed phase shifter.(b) W1 = 0.2mm, with a parametric sweep on the dimension of W2: the insertion loss and return loss of the proposed phase shifter.

III. DETERMINE THE ADJUSTED PARAMETERS OF THE LIQUID CRYSTAL SHIFTER

The phase shifter is designed with a center frequency f_c of 6.67 GHz, a relative bandwidth of 20%, and a ripple factor of 0.1 dB, within the design frequency band of 6.4 GHz to 7.1 GHz. The permittivity is 2.9, the median value of its adjustable range, to balance the variation from no voltage applied to full voltage on the liquid crystal LC. There are the adjusted dimensions as presented in Table 2. By loading these found dimensions into the currently more complex liquid crystal structure, a broadband phase shifter, whose phase is controlled by local liquid crystal, is designed, and its simulation is presented in Section IV.

TABLE II

FINAL DETERMINED PARAMETERS OF THE PROPOSED SHIFTERS (UNIT: mm)

Parameter	$S1$	$S2$	$L1$	$L2$	$W1$	$W2$	W_s	L_s
Value (mm)	0.1	0.1	6.5	6.4	0.1	0.2	0.45	0.1

IV. SIMULATED RESULTS

As seen in Fig.4, the insertion loss and phase shift range vary with the voltage applied to the liquid crystal, which changes with the permittivity of the local liquid crystal LC. The frequency sweep range is 6 GHz to 7.5 GHz, and the simulation results are shown in the Fig. 4. The design can achieve a 20% of relative bandwidth, which corresponds to a frequency range of 6.07 to 7.425 GHz. The application bandwidth is 6.4 to 7.1 GHz, and the design bandwidth is appropriately widened. Finally, under the dynamic control of the liquid crystal, an average phase shift range of 65° is realized. Meanwhile, a larger phase shift range can be achieved at higher frequencies. Due to processing limitations, the coupling gap required for strong coupling is set to 0.1 mm. In addition, no coupling enhancement is implemented in this work. Nonetheless, the average insertion loss within the design frequency band remains below 1.5 dB.

According to the reference formula of FOM given in Article [1], we list the technical characteristics achieved below in TABLE III. With in the application bandwidth of 6.4

to 7.1 GHz, the average FOM is 51.41°/dB; The average insertion loss is 1.19dB, and the maximum insertion loss is 1.92 dB. At the center frequency of 6.75 GHz, the maximum relative phase shift is 65.56° ; the maximum relative insertion loss is 0.5 dB at the center frequency.

TABLE III

SIMULATED CHARACTERISTICS OF THE PROPOSED SHIFTERS

	FOM_{av}	IL_{av}	IL_{max}	$\Delta\Phi_{fc}$	ΔIL_{fc}
Simulated	51.41°/dB	1.19 dB	1.92 dB	65.56°	0.5 dB

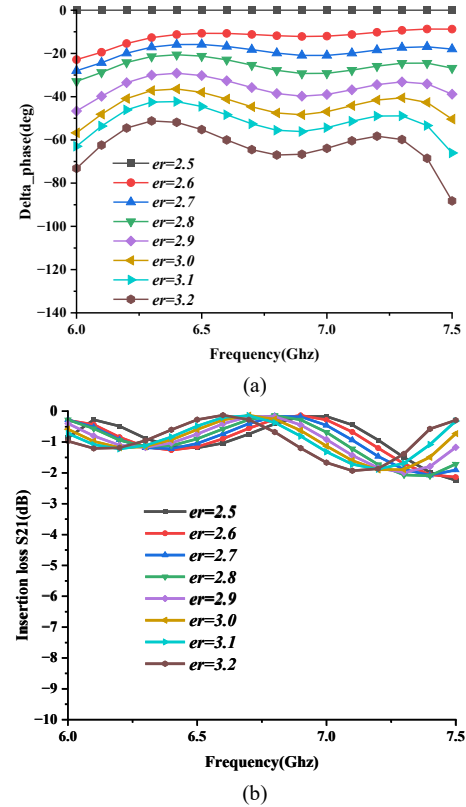


Fig. 4. The simulation result of the proposed phase shifter. (a) The phase shift difference of different dielectric constants relative to the initial dielectric constant $\epsilon_r=2.5$. (b) The insertion loss of different dielectric constants relative to the initial dielectric constant $\epsilon_r=2.5$.

V. CONCLUSION

This paper proposes a design method based on a coupled-line bandpass filter. By using this method, a liquid crystal phase shifter with dynamic tunability has been designed. By applying voltage to the liquid crystal directly below the transmission line to make it tunable, phase shifts under different relative permittivities are achieved. Simulation results show that the proposed structure can already achieve a phase shift of over 65° . The insertion loss is less than 1.5 dB, and the frequency band is centered at 6.75 GHz with a 20% relative bandwidth. Additionally, a wider phase shift range is achieved at higher frequencies. Moreover, the coupled microstrip line structure exhibits excellent integration and reconfigurability. It enables the phase shifter to be integrated into smaller devices in the future and to realize dynamic regulation of higher phase shifts.

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REFERENCES

- [1] A. Moessinger, C. Fritzsche, S. Bildik and R. Jakoby, "Compact tunable Ka-band phase shifter based on liquid crystals," in *Proc. 2010 IEEE MTT-S International Microwave Symposium*, Anaheim, CA, USA, 2010, pp. 1020-1023.
- [2] S. Kim, C. -B. Chae and B. -W. Min, "A Low-Loss Defected-Ground-Structure Based Phase Shifter and Antenna on a 4- μ m Thin Liquid Crystal Layer," *IEEE Access*, vol. 11, pp. 34952-34957, 2023.
- [3] S. Bulja, D. Mirshekar-Syahkal, M. Yazdanpanahi, R. James, S. E. Day and F. A. Fernández, "60 GHz Reflection Type Phase Shifter based on liquid crystal," in *Proc. 2010 IEEE Radio and Wireless Symposium (RWS)*, New Orleans, LA, USA, 2010, pp. 697-699.
- [4] H. Zhou, L. Guo and A. Abbosh, "Liquid Crystal Tunable Stripline Phase Shifter," in *Proc. 2023 5th Australian Microwave Symposium (AMS)*, Melbourne, Australia, 2023, pp. 3-4.
- [5] D. Wang, E. Polat, H. Tesmer, R. Jakoby and H. Maune, "Highly Miniaturized Continuously Tunable Phase Shifter Based on Liquid Crystal and Defected Ground Structures," *IEEE Microwave and Wireless Components Letters*, vol. 32, no. 6, pp. 519-522, June 2022.
- [6] L. Cai, H. Xu, J. Li and D. Chu, "High FoM liquid crystal based microstrip phase shifter for phased array antennas," in *Proc. 2016 International Symposium on Antennas and Propagation (ISAP)*, Okinawa, Japan, 2016, pp. 402-403.
- [7] E. Polat et al., "Liquid Crystal Phase Shifter Based on Nonradiative Dielectric Waveguide Topology at W-Band," in *Proc. 2019 IEEE MTT-S International Microwave Symposium (IMS)*, Boston, MA, USA, 2019, pp. 184-187.
- [8] A. Jiménez-Sáez, M. Späth, R. Neuder and R. Jakoby, "Liquid Crystal Goes RF: From Gigahertz to Terahertz," *IEEE Microwave Magazine*, vol. 26, no. 6, pp. 82-102, Jun. 2025.
- [9] Jia-Chi S. Chieh; Satish K. Sharma, "Liquid Metal, Piezoelectric, and RF MEMS-Based Reconfigurable Antennas," in *Proc. Multifunctional Antennas and Arrays for Wireless Communication Systems*, IEEE, 2021, pp. 172-197.
- [10] C. Weil, G. Luessem and R. Jakoby, "Tunable inverted-microstrip phase shifter device using nematic liquid crystals," in *Proc. 2002 IEEE MTT-S International Microwave Symposium Digest* (Cat. No. 02CH37278), Seattle, WA, USA, 2002, pp. 367-371 vol.1.