Design of a Cylindrical Conformal Liquid Crystal Phase Shifter

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Abstract: In this paper, a conformal phase shifter with cylindrical spiral based on liquid crystal material is designed for cylindrical conformal structure. By changing the dielectric constant of liquid crystal, the phase shifting range is more than 360° and can be continuously adjustable in the range of 12GHz-20GHz. At the same time, the simulation results show that the S_{11} of the phase shifter is lower than - 10dB, S_{21} is higher than -5dB. Based on the phase shifter, a 1*4 phase shifter array is simulated. The optimized results show that the phase shifter array can achieve S_{11}<-10dB, S_{21}>-6dB in range of 14GHz-16GHz, which has certain practical value.

1. Introduction

With the development of modern electronic information technology, the requirements for phased array antenna are higher and higher. The planar phased array antenna solves the problems of limited gain and difficult wave scanning of single antenna to a certain extent. However, for satellite borne, airborne and missile borne occasions, the antenna is often required to have the ability of conformal with the carrier. Nowadays, with the emergence of various excellent beam forming algorithms and antenna design methods [1-3], as well as the improvement of material technology and processing technology, conformal phased array antenna is in the second rapid development period, and the research on conformal phased array is attached great importance at home and abroad [4-5].

As the core component of phased array unit, phase shifter plays an important role in the performance of the whole array. Phase shifters with low loss, miniaturization and low cost are urgently needed in phased array for beam shaping and beam control. In addition, the current phase shifter design is basically limited to the planar structure [6-8]. The design of a new conformal phase shifter can not only fit in with the development of conformal phased array, but also be a scheme of miniaturization and integration of phase shifter.

Liquid crystal is a kind of electrically controlled tunable material with both crystal anisotropy and liquid fluidity, which is easy to realize conformal design. The application research of liquid crystal microwave tunable devices based on this technology covers important research fields such as tunable filter [9], reconfigurable antenna [10], and adjustable phase shifter [11-14].

2. Theory of Liquid Crystal Phase Shifter

Due to the dielectric anisotropy of liquid crystal materials, the axial direction of the liquid crystal molecules can be changed by applying an external electric field, thus changing the dielectric constant of the material, so it has tunability. Specifically, the tunability of liquid crystal materials is that when they are used as dielectric substrates, the resonant frequency will change with the change of dielectric constant of liquid crystal materials, which is also the basis of liquid crystal materials as tunable materials.

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An ideal parallel plate capacitor can be used to simulate the response of the liquid crystal layer in the liquid crystal phase shifter to the applied electric field, and the corresponding length of the phase shifter can be calculated according to the required phase shifting amount.

Under ideal conditions, there is a uniform electric field between the two plates of the parallel plate capacitor, which can ensure that the orientation of the liquid crystal in the parallel plate is consistent under the bias state. In the face-to-face parallel plate capacitor, the capacitance value can be calculated by the following formula:

$$C = \frac{\varepsilon d}{4\pi kq} \tag{1}$$

The core of liquid crystal phase shifter is to adjust the dielectric constant of the medium in the process of electromagnetic wave transmission, so as to change the capacitance, and then change the phase-shift constant of electromagnetic wave in the transmission process:

$$\beta = \omega\sqrt{LC} = \omega\sqrt{\mu\varepsilon} \tag{2}$$

where β and $\beta_{\perp}$ are the phase shift constants when the liquid crystal is in two states of bias and alignment, respectively. When the dielectric constant of the liquid crystal changes, the differential phase shift is:

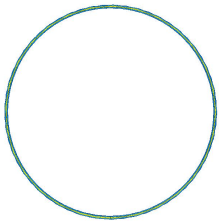
$$\Delta\phi = l\left(\beta - \beta_{\perp}\right) = l\frac{\omega}{c_0}\left(\sqrt{\varepsilon} - \sqrt{\varepsilon_{\perp}}\right) \tag{3}$$

where l corresponds to the physical length of the phase shifter and c_0 is the speed of light propagation in vacuum. The maximum phase shift of the phase shifter is determined by the length of the phase shifter and the variation of the dielectric constant.

3. Structure Design of Phase Shifter

Aiming at the widely used cylindrical structure, based on the conventional transmission line-up liquid crystal phase shifter, a cylindrical spiral structure liquid crystal phase shifter is designed. The working frequency is 15GHz. The model diagram is shown in Figure 1.

(a)Side view



(b)Top view

Figure 1: Structure of cylindrical helical liquid crystal phase shifter.

The parameter equation of the cylindrical spiral structure is as follows:

$$\begin{bmatrix} x = r\cos(\theta) \\ y = r\sin(\theta) \\ z = b\theta \end{bmatrix} \quad (4)$$

where r is the radius of the conformal cylinder and is the rising distance of helix per circle. The internal structure from bottom to top can be roughly divided into: lower substrate, ground plane, liquid crystal layer, transmission line, and upper substrate. The transmission line circuit is etched on the lower surface of the upper substrate in contact with the liquid crystal material, and the energy is fed in from the lower end and fed out from the upper end. The liquid crystal is installed between the upper and lower substrates, and the dielectric constant of the liquid crystal is controlled by the applied voltage of the grounded metal layer, thus realizing the phase shift function. The main structural parameters are shown in the Table 1:

Table 1: Design parameters and their values.

Parameters	hs	hlc	r	b	wps	lx	t
Value(mm)	0.254	0.254	30	3	1.385	4.85	0.035

The S parameters of the phase shifter are obtained by simulation, as shown in Figure 2.

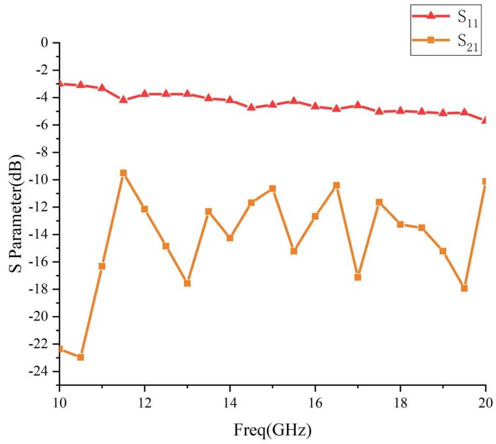


Figure 2: S parameter of phase shifter.

It can be seen that in the range of 12GHz-20GHz, S11 is lower than -10dB, S21 is higher than -5dB, and the curve is relatively stable. And the phase shift is shown in the Figure 3.It can be seen that in the range of dielectric constant from 2.5 to 3.3, the phase shift increases with frequency, and the phase shift range exceeds 360° at 12GHz. At the designed operating frequency of 15GHz, the phase shifting range can reach 794° which is far beyond the requirement of 360° phase shifting.

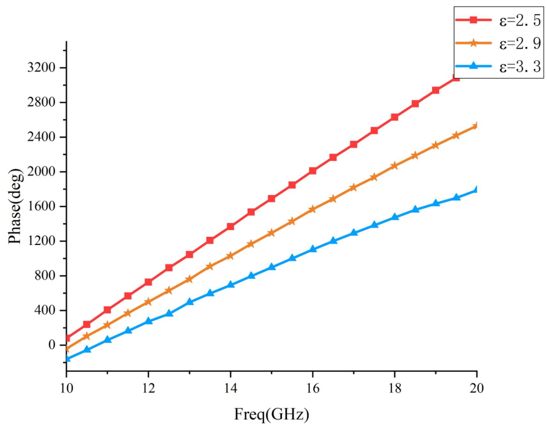
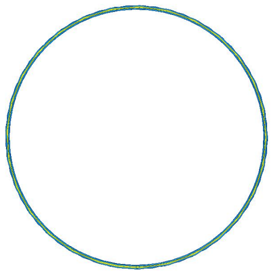


Figure 3: Phase shifting range of phase shifter.

4. Design of Phase Shifter Array

Based on the designed phase shifter structure, a 1*4 phase shifter array is designed to verify the feasibility of its application in conformal phased array antenna. The simulation model is shown in Figure 4.

(a)Side view.



(b)Top view.

Figure 4: Structure of 1*4 cylindrical helical liquid crystal phase shifter.

The phase shifter spacing is dx. Since the operating frequency is 15GHz, the initial value dx = 10mm is taken when the array elements are arranged according to the half wavelength. The simulation is carried out with dx as the optimized parameter, the results are shown in Figure 5.

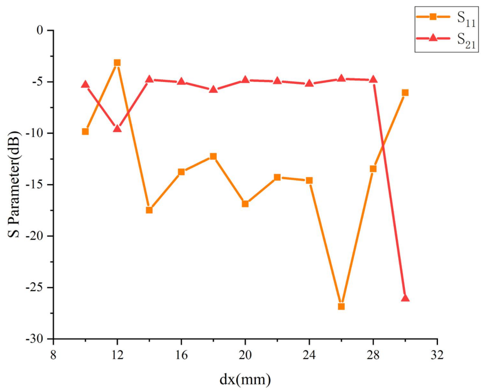
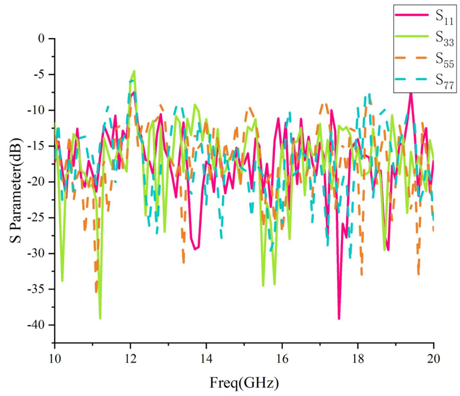
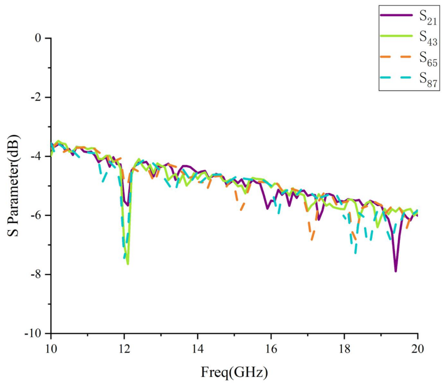


Figure 5: S parameter varies with array spacing dx.

After comprehensive comparison of S_{11} and S_{21}, taking dx=14mm, combined with other optimization parameters, the simulation results are shown in the Figure 6. It can be seen that S_{11} is less than -10dB, and S_{21} is greater than -6dB in the range of 14GHz-16GHz.



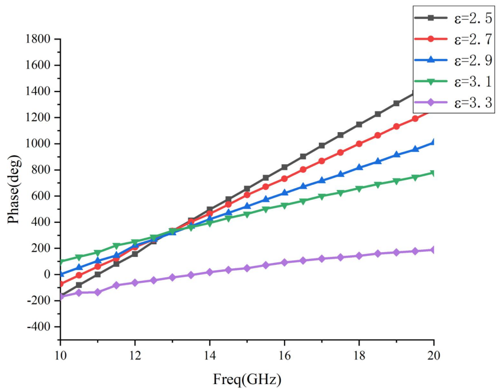
(a)



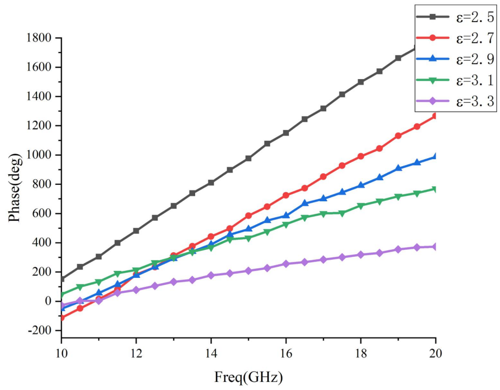
(b)

Figure 6: Optimized S parameters of 1*4 phase shifter array.

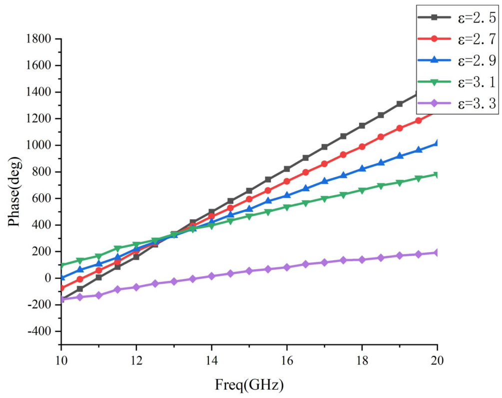
At this time, the phase-shifting range of each phase shifter is shown in Figure 7. It can be seen that at 15GHz, the liquid crystal dielectric constant changes from 2.5 to 3.3, and the phase-shifting range is greater than 360° to meet the requirements of the phase shifter.



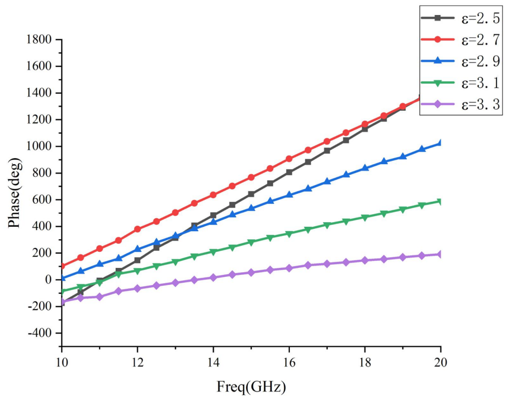
(a)Phase shifter 1.



(b)Phase shifter 2.



(c)Phase shifter 3.



(d)Phase shifter 4.

Figure 7: Phase shifting of phase shifter array:

(a)Phase shifter 1 (b) Phase shifter 2 (c) Phase shifter 3 (d) Phase shifter 4.

5. Conclusions

Based on the conventional transmission line liquid crystal phase shifter, a new cylindrical conformal phase shifter is designed for conformal phased array antenna. The design frequency is

15GHz. The simulation results show that the phase shifter can achieve a phase shift much higher than 360° in the range of dielectric constant from 2.5 to 3.3. Based on the modified phase shifter, a 1*4 phase shifter array simulation is carried out. After optimization, S11<-10dB, S21>-6dB in the range of 14GHz-16GHz can be realized, and the phase shift of each element is greater than 360° and can be further applied to conformal phased array antenna.

Acknowledgments

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References

[1] Wenhua Yu, N. Farahat and R. Mittra, "Application of FDTD method to conformal patch antennas," IEEE Antennas and Propagation Society International Symposium. 2001 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No.01CH37229), Boston, MA, USA, 2001, pp. 362-365 vol.2, doi: 10.1109/APS.2001.959738.

[2] Mang He and Xiaowen Xu, "Closed-form solutions for analysis of cylindrically conformal microstrip antennas with arbitrary radii," in IEEE Transactions on Antennas and Propagation, vol. 53, no. 1, pp. 518-525, Jan. 2005, doi: 10.1109/TAP.2004.838772.

[3] F. Zhao, K. Xiao, H. Qi, S. Chai and J. Mao, "Preconditioned alternate projections method to synthesise conformal array," in Electronics Letters, vol. 47, no. 13, pp. 735-736, 23 June 2011, doi: 10.1049/el.2011.0872.

[4] S. Xiao, S. Yang, H. Zhang, Q. Xiao, Y. Chen and S. Qu, "Practical Implementation of Wideband and Wide-Scanning Cylindrically Conformal Phased Array," in IEEE Transactions on Antennas and Propagation, vol. 67, no. 8, pp. 5729-5733, Aug. 2019, doi: 10.1109/TAP.2019.2922760.

[5] J. -J. Peng, S. -W. Qu, M. Xia and S. Yang, "Wide-Scanning Conformal Phased Array Antenna for UAV Radar Based on Polyimide Film," in IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 9, pp. 1581-1585, Sept. 2020, doi: 10.1109/LAWP.2020.3011412.

[6] W. Kim, J. P. Thakur, H. Yu, S. Choi and Y. Kim, "Ka-band hybrid phase shifter for analog phase shift range extension using 0.13-μm CMOS technology," 2010 IEEE International Symposium on Phased Array Systems and Technology, Waltham, MA, 2010, pp. 603-606, doi: 10.1109/ARRAY.2010.5613306.

[7] H. Lee and B. Min, "W-Band CMOS 4-Bit Phase Shifter for High Power and Phase Compression Points," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 62, no. 1, pp. 1-5, Jan. 2015, doi: 10.1109/TCSII.2014.2362732.

[8] Q. Zhang, C. Yuan and L. Liu, "Studies on mechanical tunable waveguide phase shifters for phased-array antenna applications," 2016 IEEE International Symposium on Phased Array Systems and Technology (PAST), Waltham, MA, 2016, pp. 1-3, doi: 10.1109/ARRAY.2016.7832555.

[9] R. Follmann et al., "Liquida-Sky — A tunable liquid crystal filter for space applications," 2013 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), Torino, 2013, pp. 90-93, doi: 10.1109/APWC.2013.6624872.

[10] G. Perez-Palomino et al., "Design and Experimental Validation of Liquid Crystal-Based Reconfigurable Reflectarray Elements With Improved Bandwidth in F-Band," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 4, pp. 1704-1713, April 2013, doi: 10.1109/TAP.2013.2242833.

[11] A. Moessinger, C. Fritzsch, S. Bildik and R. Jakoby, "Compact tunable Ka-band phase shifter based on liquid crystals," 2010 IEEE MTT-S International Microwave Symposium, Anaheim, CA, 2010, pp. 1020-1023, doi: 10.1109/MWSYM.2010.5517405.

[12] C. Fritzsch et al., "Continuously tunable W-band phase shifter based on liquid crystals and MEMS technology," 2011 6th European Microwave Integrated Circuit Conference, Manchester, 2011, pp. 522-525.

[13] L. Cai, H. Xu, J. Li and D. Chu, "High FoM liquid crystal based microstrip phase shifter for phased array antennas," 2016 International Symposium on Antennas and Propagation (ISAP), Okinawa, 2016, pp. 402-403.

[14] H. Tesmer, R. Reese, E. Polat, R. Jakoby and H. Maune, "Dielectric Image Line Liquid Crystal Phase Shifter at W-Band," 2020 German Microwave Conference (GeMiC), Cottbus, Germany, 2020, pp. 156-159.