Design of a Terahertz Phased Array Based on Liquid Crystal Phase Shifter

Kai Zhu[1,a,*], Tianming Bai[1,b], Weiyi Zhang[1,c] and Di Jiang[1,2,d]

[1]School of Information and Communication Engineering,University of Electronic Science and Technology of China, Chengdu ,611731, China

[2]School of Communication Engineering, Guilin University of Electronic Technology, Guilin, 541004, China

a. zhukai1278@163.com, b. tianyumingfeng@163.com, c. wyzhang_98@163.com, d, merryjiangdi@163.com

**Kai Zhu*

Keywords: Liquid crystal, Terahertz phased array, Phase shifter.

Abstract: In this paper, a terahertz phased array operating at 0.22THz is designed based on the integration of liquid crystal phase shifter, antenna radiation unit and power division network. The maximum scanning angle can reach ±10° by electrically controlling the liquid crystal phase shifter. In the simulation, the antenna array shows a half power beam width of 12° on the E-plane, and the gain is higher than 14dBi at 220GHz, and the sidelobe level is about -9dB. The antenna array shows good matching, and the return loss is below -10dB in the bandwidth up to 35GHz.

1. Introduction

In recent years, with the further development of terahertz radiation source and detector, and the continuous breakthrough of terahertz antenna, new modulator, waveguide, filter and other functional devices, the rapid development of terahertz in the field of communication has been promoted. Although terahertz has many advantages in band, the practical process of terahertz radar, communication and imaging system is very slow, especially the lack of broadband and low insertion loss terahertz phased array, which seriously delays the practical process of communication system and radar in terahertz band [1-2].

Because the electrodes can be easily integrated into the open structure of dielectric waveguides, dielectric waveguides are a promising alternative to conventional waveguides. A wide variety of dielectric waveguides provide a lot of freedom for the design of intelligent millimeter wave devices, such as tunable phase shifters, filters and tunable antennas.

As a core part of phased array antenna, phase shifter determines the beam formed by signal phase in each antenna unit. There are two major trends in the development of terahertz phase shifters. One is to explore new special materials and utilize the change of material properties to cause the change of phase constant, so as to produce phase shift, such as liquid crystal phase shifter and graphene phase shifter; the other is utilizing new advanced technology to produce phase shifter, such as Micro Electro Mechanical Systems (MEMS) [3] and Monolithic Microwave Integrated

Circuit (MMIC)based on integrated technology [4]. Compared with the expensive MEMS and MMIC, it is more meaningful to explore new terahertz phase shifters with special materials.

With the control of applied voltage, the dielectric constant tensor of liquid crystal changes accordingly. The electromagnetic properties of liquid crystal are very stable in terahertz band [5], and the dielectric loss can be maintained at a low level even when the frequency increases.

All in all, Liquid crystal material is used as the control medium of terahertz phased array. The optical path of terahertz through liquid crystal material is changed by applied voltage, resulting in phase difference, thus realizing the function of beam deflection of phased array [6].

This paper presents a design of terahertz phased array based on liquid crystal phase shifter. The phased array adopts antenna radiation unit, electronically controlled liquid crystal phase shifter and power division network integrated design. The design reflects the light weight and integrated characteristics of the dielectric waveguide, avoiding the cumbersome assembly.

2. Liquid Crystal Theory and Technology

The properties of liquid crystal materials in THz band are mainly determined by the torsion and vibration modes of liquid crystal molecules, and the absorption mainly comes from the torsion of benzene ring in the short axis direction. Under reasonable design, the orientation of liquid crystal molecules presents a uniform arrangement, which is called nematic liquid crystal, which shows dielectric anisotropy and refractive index anisotropy. In this paper, we use dielectric image line (DIL) structure to make the liquid crystal molecules in a certain direction. Nematic liquid crystal molecules are rod-shaped and oriented in order. They can be regarded as uniaxial crystals in terms of optical properties. There are two different dielectric constants $\varepsilon_{//}$ and $\varepsilon_{\perp}$ in the direction parallel to and perpendicular to the optical axis, and the dielectric anisotropy is expressed as $\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$. It is found that the long axis of the liquid crystal molecules is parallel to or perpendicular to the electric dipole moment (the direction of the electric field) [7]. Referring to [8], GT3-23001 liquid crystal mixture provided by Merck KGaA has been proved that the material properties are almost constant millimeter wave to several terahertz. It has the following electrical properties at 19 GHz: $\varepsilon_{\perp} = 2.41$, $\varepsilon_{//} = 3.19$, $\tan\delta_{\perp} = 0.0143$ and $\tan\delta_{//} = 0.0035$.

3. Design of the Phased Array

3.1. Multimode Interference Power Divider

First of all, we design a multimode interference (MMI) power divider. The working principle of the MMI power divider is based on the self-imaging effect of multimode waveguide [9]. Through coherent interference, one or more images of the input field will be generated periodically along the propagation direction of the waveguide. The MMI power divider has the advantages of good power distribution uniformity, compact structure, low insertion loss and wide frequency band.

These modes can propagate in the multimode waveguide because of the self-imaging effect and the superposition of all modes. At any position in the wave propagation direction, the phase of different modes moves relatively, and the phase relationship between different modes is no longer the same as that of incident mode, which makes the transverse distribution of light field at different positions of multimode waveguide different from that at the beginning of multimode waveguide.

$$\beta_0 - \beta_v \approx \frac{v(v+2)\pi}{3L\pi}, v \in N \ [10] \tag{1}$$

where, β_0 and β_v are the propagation constants of the zero order mode and the v order mode, respectively. The beat length between lower modes is defined as:

$$L_\pi \frac{\pi}{\beta_0 - \beta_v} \approx \frac{4\sqrt{\varepsilon_r} W^2}{3\lambda_0} \quad [10] \tag{2}$$

where, λ_0 is the free space wavelength, ε_r is the relative dielectric constant, W is the effective width of multimode waveguide.

The length of the one-four power divider designed by Rexolite 1422 (the dielectric constant is 2.53) is $L_4 = \frac{3L_\pi}{16}$. The structure diagram is shown in Figure 1. In order to reduce the parasitic radiation as much as possible, the corner of the MMI power divider is curved at 80 degrees. The length of the multimode interference power divider is l_{MMI} , the arc radius of the starting end is r , the width of the port is a , and the distance between the terminal ports is d .

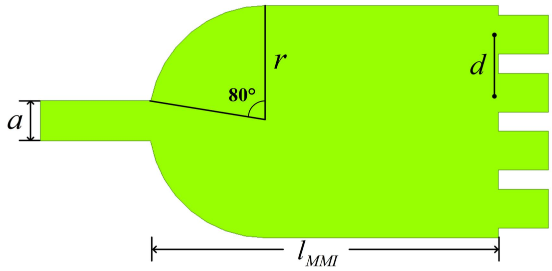

Figure 1: Multimode interference power divider.

3.2. Dielectric Image Line Liquid Crystal Phase Shifter

Dielectric image line (DIL) is a kind of planar structure, which aims to reduce the physical size of dielectric waveguide by using ground plane as mirror surface and mechanical load [11]. The larger electrode area makes the bias field more uniform.

The basic electric field mode produces an electric field polarization orthogonal to the ground plane. In this case, the tunable liquid crystal material loaded by the DIL structure can interact well with the propagating wave. Due to the low field strength near the ground plane, the bias electrode has little effect on the propagation wave. The width of the parallel polarized DIL structure is a . The cross section of the structure is shown in Figure 2. The structure includes a long rod-shaped Rexolite 1422, a liquid crystal cavity cut out in the rod-shaped Rexolite 1422, a FR-4 substrate carrying Rexolite 1422 and welding the lower bias electrode, and a FR-4 substrate welding the upper bias electrode.

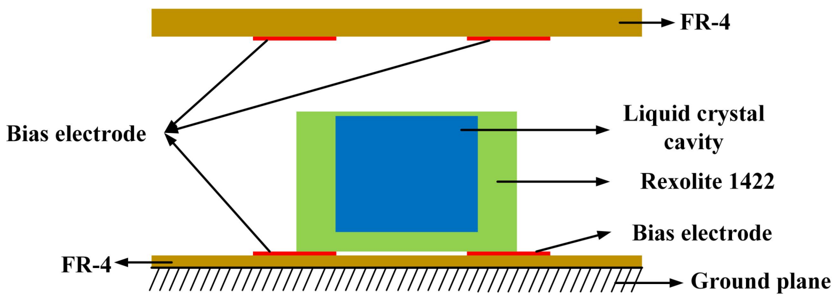

Figure 2: Structure of dielectric image line based on liquid crystal.

By applying voltage to the upper electrode and grounding the lower electrode, a longitudinal electric field formed between the upper and lower substrates as shown on the left side of Figure 3. At this time, the liquid crystal molecules are arranged vertically, and the dielectric constant is $\varepsilon_{\perp}$. On the contrary, by applying voltage to the right electrode and grounding the left electrode, a quadrupole field formed between the upper and lower substrates as shown in the right side of Figure 3. Most of the liquid crystal molecules are arranged horizontally, so the effective dielectric constant is $\varepsilon_{//}$. The length and width of electrode are 6.8mm and 0.25mm, respectively.

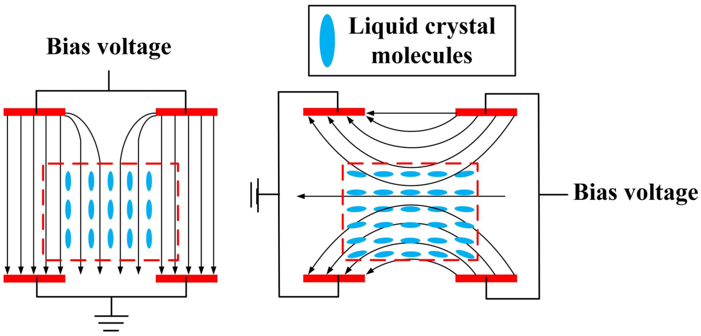

Figure 3: Schematic diagram of bias field of dielectric image line structure.

3.3. Dielectric Rod Antenna

Due to its high gain and low mutual coupling, dielectric rod antenna is very suitable for radiation element of array antenna. Considering increasing the working bandwidth of dielectric rod antenna, the larger the dielectric constant of the material is, the steeper the fundamental mode dispersion curve is and the narrower the bandwidth is. Considering comprehensively, Rexolite 1422, the same material as the dielectric phase shifter, is selected. As shown in Figure 4, the four tapered dielectric rod antennas are designed with two different lengths, l_1 and l_2 respectively, to compensate for the phase difference caused by the power divider.

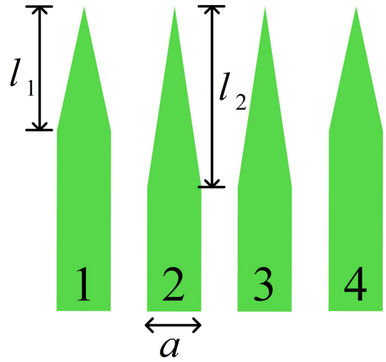

Figure 4: Dielectric rod antennas of different lengths.

The gain of the antenna as a medium in the terahertz band will often be adjusted appropriately according to the needs of the antenna. For example, in most cases, the length of the dielectric rod antenna should not be too long because the structure of the dielectric rod antenna needs to be inserted into the waveguide, otherwise it will incline when inserting. The bottom diameter of the dielectric rod antenna can be appropriately increased compared with the optimal gain condition, which can increase the bandwidth of the antenna to a certain extent, but the main lobe gain will be reduced. After simulation and optimization, the ground width of the antenna is determined to be a.

4. Simulation Results of Phased Array

In Ansoft HFSS, a model of phased array as shown in Figure 5 is built, and DIL liquid crystal phase shifter structure is shown in the dotted line box. The parameters in the model are listed in Table 1.

Table 1: Parameters of the simulation (unit: mm).

a	d	r	l_{MMI}	l_1	l_2
1	1.5	3	11	3.2	5.8

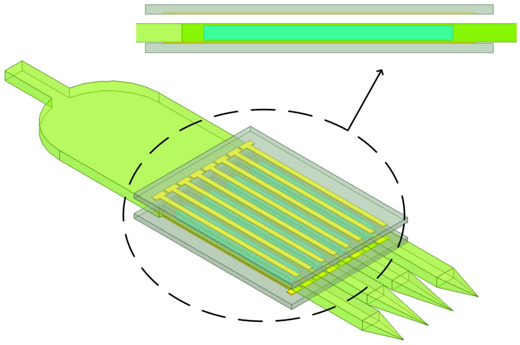

Figure 5: Simulation model diagram.

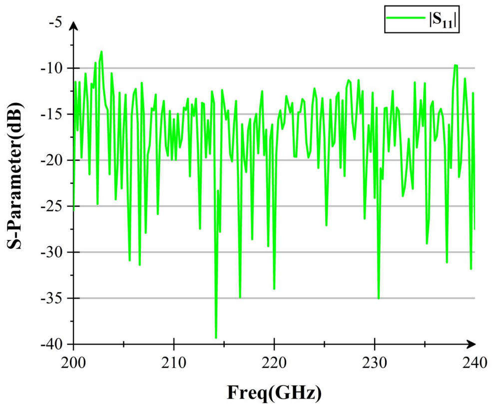

Figure 6: Simulated reflection coefficient of the phased array.

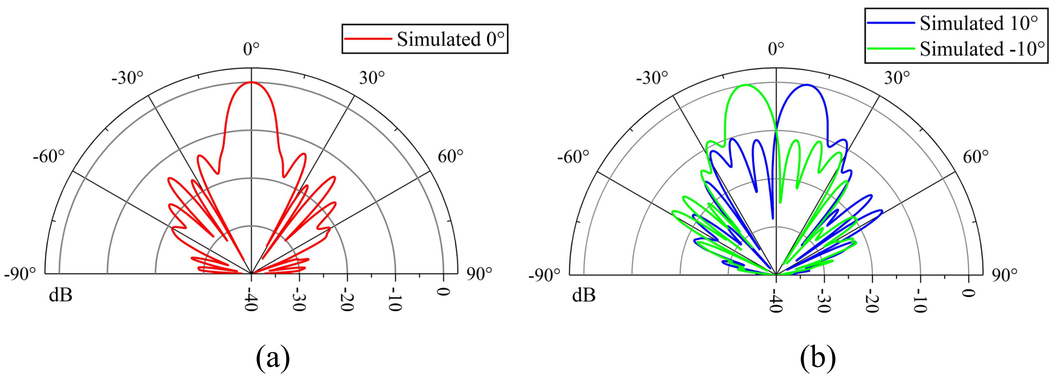

Figure 7: Simulated antenna pattern in the E-plane.

In the frequency range of 200GHz-240GHz, the simulation results of reflection coefficient of phased array antenna are shown in Figure 6. Due to the close and continuous connection of each part, there is very little return loss. It can be seen from the figure that the reflection coefficient S_{11} is better than -10dB in the bandwidth of 203GHz-238GHz. At 220GHz, as shown in Figure 7, the maximum steering angle of ±10° is realized by simulation, and the antenna pattern on the E-plane is described in the figure. The main part of the sidelobe is less than -12dB, only the sidelobe level (SLL) of the first sidelobe is -9dB. When the dielectric constant of liquid crystal is $\varepsilon_{\perp}$ and $\varepsilon_{//}$, the antenna gain is 14.5dBi and 15.1dBi, respectively.

5. Conclusions

The proposed terahertz phased array based on liquid crystal phase shifter has the characteristics of small volume, light weight and high frequency of liquid crystal phase shifter, the excellent electrical performance of dielectric rod antenna and the low loss and uniform distribution of MMI power divider. At the same time, using the existing Rexolite 1422 microwave plastic processing technology, the cost of phased array antenna is greatly reduced, the stable dielectric performance in terahertz band is ensured, and the miniaturization and full dielectric conduction of electromagnetic wave are realized.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 61871086); the Science and Technology Support Project of Sichuan Province (2019JDRC0071, 2019YFG0127, 2019GFW125, 2019YFG0431, 2019YFG0499, 2020YFG0043), Guangxi Key Laboratory of Wireless Wideband Communication and Signal Processing (GXKL06190208) and the International Co-operation Support Plan of Sichuan Province (2019YFH0013); Applied Basic Research Project of Sichuan Province (2018JY0581).

References

[1] Kowerdziej R, Jaroszewicz L, Olifierczuk M. Experimental Study on Terahertz Metamaterial Embedded in Nematic Liquid Crystal. Applied Physics Letters,2015,106(9):092905.

[2] Wang C T, Wu C L, Zhang H W. Polarization-independent 2 pi Phase Modulation for Terahertz Using Chiral Nematic Liquid Crystals. Optical Materials Express,2016,6(7):2283-2290.

[3] Shah U, Decrossas E , Jung-Kubiak C, et al. Submillimeter-Wave 3.3-bit RF MEMS Phase Shifter Integrated in Micromachined Waveguide. IEEE Transactions on Terahertz Science &Technology, 2016:1-10.

[4] Zaiden D M, Grandfield J E, Weller T M, et al. Compact and Wideband MMIC Phase Shifters Using Tunable Active Inductor-Loaded All-Pass Networks. IEEE Transactions on Microwave Theory & Techniques, 2017, PP(99):1-11.

[5] Li X, Lin L, Wu L S. A Bandpass Graphene Frequency Selective Surface with Tunable Polarization Rotation for THz Applications. IEEE Transactions on Antennas & Propagation, 2017,65(2):662-672.

[6] Lin Y T, Jau H C, Lin T H. Polarization-independent Rapidly Responding Phase Grating Based on Hybrid Blue Phase Liquid Crystal. Journal of Applied Physics, 2013,113(6):063103.

[7] Sun S Y, Yu X, Wang P J, et al. Electronically Tunable Liquid-Crystal-based F-Band Phase Shifter[J]. IEEE Access, 2020, PP(99):1-1.

[8] Weickhmann C, Jakoby R, Constable E, et al. Time-domain spectroscopy of novel nematic liquid crystals in the terahertz range. International Conference on Infrared. IEEE, 2013.

[9] Reese R, Jost M, Nickel M, et al. A Fully Dielectric Light-Weight Antenna Array Using a Multimode Interference Power Divider at W-Band. IEEE Antennas & Wireless Propagation Letters, 2017, PP:1-1.

[10] Soldano L B, Pennings E C M. Optical multi-mode interference devices based on self-imaging: principles and applications. Journal of Lightwave Technology, 1995, 13(4):615-627.

[11] Tesmer H, Reese R, Polat E, et al. Dielectric Image Line Liquid Crystal Phase Shifter at W-Band. 2020 German Microwave Conference (GeMiC). IEEE, 2020.