Liquid-Crystal-Based Discrete Phase Shifter for Improving Response Speed

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Abstract

Liquid crystals (LCs) have a characteristic in which the dielectric constant changes depending on the rearrangement of the liquid crystal molecules according to the voltage. Therefore, they are widely used in research on various circuits in the microwave frequency band utilizing the variable dielectric constant. Research on the phase shifter, a key element of beamforming antennas, is active, and many studies are being conducted to improve performance such as propagation loss, response speed, and phase difference controllable range. This paper proposes an idea to improve the response speed, and the speed at which liquid crystal molecules align greatly varies depending on the size of the applied voltage. Although it is affected by the size of the liquid crystal cell gap, the alignment speed of the liquid crystal molecules becomes much faster as the size of the applied voltage increases, and the response speed increases by more than 10 times as the applied voltage decreases. In other words, the response speed deviation is large depending on the desired phase value. Therefore, in this paper, we propose a design method to reduce the response speed deviation according to the phase difference that occurs due to the use of multiple levels of voltage in a liquid crystal-based phase shifter, and through actual experiments, we prove that the absolute response speed can be improved while reducing the response time deviation according to the phase value to less than 1/3 compared to the existing method.

Author Keywords

Liquid crystal, dielectric anisotropy, response time, phase shifter, beamforming array

1. Introduction

6G is the next-generation communication technology that offers faster transmission speeds, lower latency, and enhanced connectivity compared to 5G. Beamforming technology maximizes communication efficiency by concentrating radio waves in specific directions and plays a critical role in addressing signal attenuation and interference issues in the high-frequency band. Therefore, beamforming array antennas are essential for 6G systems [1-3]. The phase shifter, a key component of beamforming array antennas, has recently become a focus of research, particularly those based on liquid crystal (LC), known for its low-loss characteristics in high-frequency bands [4-7]. The primary performance metrics of phase shifters include transmission loss, phase shift range, response time, and driving voltage. However, research efforts are actively being made to overcome the relatively slow response speed of liquid crystals compared to semiconductor devices [8-11].

In this paper, we propose a design method to enhance the response speed of liquid crystals in phase shifters by modifying the biasing method applied to the liquid crystal. Through experiments, we observed the performance changes resulting from this approach.

2. LC-Based Discrete Phase Shifter Design

Liquid crystal (LC) molecules change their alignment direction depending on the applied bias voltage. Since the change in molecular alignment changes the permittivity of the LC, a phase shifter for a microwave frequency band can be designed by utilizing the permittivity conversion characteristics. Figure 1 is an example of an LC cell created by positioning electrode plates above and below the LC, and applying a bias voltage to both ends. When 0 V is applied between the upper and lower electrodes, the LC molecules lie in a direction parallel to the electrode plates, whereas when a voltage such as V_{bias1} or V_{bias2} is applied to both ends of the LC, the LC can be seen standing parallel to the direction of the electric field, that is, perpendicular to the electrode plates. At this time, the liquid crystal molecules that were lying down gradually stand up depending on the magnitude of the bias voltage, and accordingly, the permittivity also provides a continuous value.

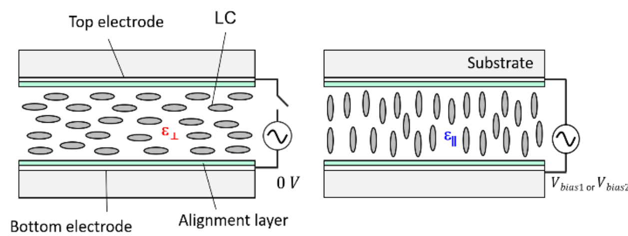

Figure 1. Liquid crystal molecules rearrange themselves according to bias voltage.

Figure 2 shows a phase shifter with an upper substrate with a meander line designed to obtain more phase delay in a limited space and a lower substrate with a ground plane. A spacer film is inserted in the middle layer of the upper and lower substrates to allow for the injection of LC, and it is designed to have an appropriate cell gap. Figure 2(a) is a phase shifter that applies a bias to obtain a conventional continuous phase difference, and Figure 2(b) is a circuit proposed in this paper, which is a phase shifter designed to get a discrete phase to improve the response speed.

LC molecules align quickly when the voltage exceeds a certain threshold. However, when a voltage below the threshold is applied, the molecules readjust and stabilize, sometimes taking several seconds. To achieve faster response time, we propose a binary driving method for the LC-based phase shifter as shown in Figure 2(b). By physically dividing the phase shift region into several sections and rapidly readjusting the LC molecules using only high driving voltages above the critical threshold, the response time variation for different phase values can be minimized.

The proposed structure, in order to apply bias separately by region, applies 0 V to the upper meander line, and divides the ground plane into two or more regions (ex. V_{bias1}, V_{bias2}) so that the bias voltage can be applied separately. At this time, a bandpass filter is designed and inserted into the separated regions of the ground plane to minimize RF signal transmission loss in the desired frequency range.

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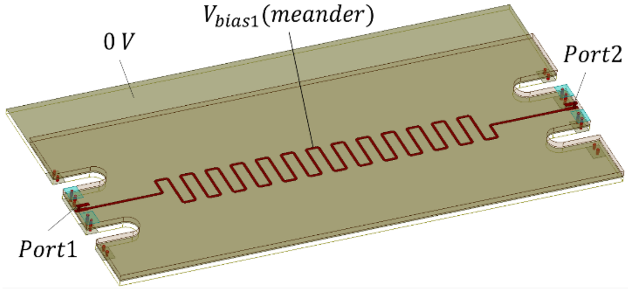
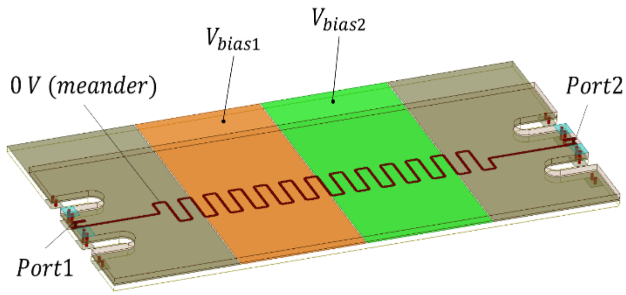


(a)



(b)

Figure 2. (a)LC-based phase shifter using the conventional continuous voltage application method (b)Discrete phase shifter that uses only high voltage bias greater than threshold value.

3. Experimental Results

Liquid crystal-based phase shifters were fabricated for two different configurations: one that uses continuous bias voltages to obtain the desired phase shift, and the other uses only one high voltage but physically divides the region to have different phase shifts and applies the voltage to the desired region.

Table 1 presents the results of measuring the response time for the two phase shifters. First, to obtain a phase difference of 35 degrees, V_{low} value must be applied to V_{bias1} in the conventional continuous bias circuit, but since V_{low} is a value below the threshold voltage, the response speed of the LC molecules is very slow, so it takes time corresponding to τ_0 for the alignment of the LC molecules to stabilize. On the other hand, to obtain a phase difference of 35 degrees using the proposed discrete bias method, V_{high} only needs to be applied to the V_{bias1} region. Since V_{high} is a value far exceeding the threshold voltage, the response speed of the LC molecules is fast, so the LC stabilizes in just $0.2\tau_0$ seconds, which is only 1/5 of the time of the conventional continuous method. Even when trying to obtain a phase difference of 70 degrees, the conventional method takes about $0.64\tau_0$ seconds, while the discrete method can obtain the desired phase difference of 70 degrees in just $0.22\tau_0$ seconds. In addition, the response time deviation according to the phase value was compared. When using continuous bias, the response time deviation is about 36 % for the phase difference of 35 degrees and 70 degrees, while the discrete method shows a response time deviation of less than 10 %.

Table 1. Measured results of the response time of phase shifters using two different biasing methods.

Phase change (°)	Continuous bias	τ_{on} (s)	Discrete bias	τ_{on} (s)
0° → 35°	$V_{bias1} = V_{low}$	τ_0	$V_{bias1} = V_{high}$ $V_{bias2} = 0\,V$	$0.2\tau_0$
0° → 70°	$V_{bias1} = V_{mid}$	$0.64\tau_0$	$V_{bias1} = V_{high}$ $V_{bias2} = V_{high}$	$0.22\tau_0$

4. Conclusion

When trying to manufacture a phase shifter based on liquid crystals, a bias method was proposed to improve the response speed of the LCs. In particular, an improvement technique for the time it takes for the LC molecules to stabilize when the bias is applied is discussed. Using a sufficiently high voltage as a bias to align the LC molecules parallel to the electric field, compared to an intermediate voltage value that aligns the LC molecules obliquely, is a method to minimize the response time. Therefore, in this paper, the phase shifter area was strategically divided in advance to obtain the desired phase difference, and then a high driving voltage that can quickly adjust the alignment of the LC molecules was used to implement the response speed of the phase shifter more than 5 times faster. This is an important function that directly affects the beam direction control speed of the beamforming array antenna, and can be said to be a result that shows the possibility of an LC-based phase shifter.

5. Acknowledgements

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