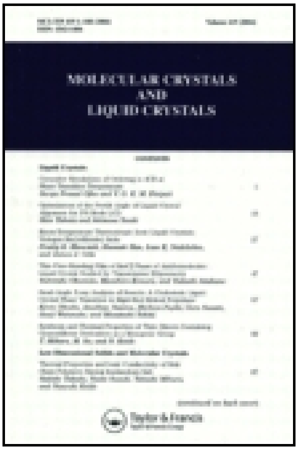

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Two types of microwave variable phase shifters of a coplanar waveguide with float electrodes on both sides and a float electrode on one side using ferroelectric liquid crystal are discussed. The measured phase shift is proportional to the frequency of the microwave according to the theory, and the measured phase in the both-sided-electrode device is larger than that in the one-sided-electrode device. The measured phase shift increases with increasing applied voltage in both devices. The response time of the both-sided-electrode device is less than 1 ms above 120 V, and a very high speed variable phase shifter is realized.

Keywords: coplanar waveguide; ferroelectric liquid crystal; microwave phase shifter; variable delay line

INTRODUCTION

Microwave-tunable components, such as variable phase shifters and filters, have attracted considerable attention for use in satellite broadcasting and mobile communications. On the other hand, liquid crystals have a large anisotropy in dielectric permittivity in the microwave and millimeter-wave regions, and therefore, microwave and millimeter-wave

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applications using liquid crystals have been reported [1–4]. Among them, microwave phase shifters using liquid crystals have mainly been studied using nematic liquid crystal and a microstrip line structure [5–7]. In such cases, there is a serious problem about the response time, especially when the voltage is removed. For the improvement of response time, the use of a dual-frequency switching-mode nematic liquid crystal, a membrane impregnated with nematic liquid crystal and a polymer-dispersed nematic liquid crystal, has been reported [8–10].

On the other hand, ferroelectric liquid crystal possesses spontaneous polarization and exhibits high switching speed [11]. A variable delay line of a microstrip line structure using ferroelectric liquid crystal was first reported by Fujikake *et al.* [12], and we have already discussed the response time [13]. The response speed in this case is, of course, faster than when nematic liquid crystal is used, but is not sufficiently fast because of the unwinding and winding of a helical structure in the ferroelectric liquid crystal.

Recently, the microwave phase shifter of a coplanar waveguide with float electrodes using nematic liquid crystal has been reported to improve the response time [14]. In this study, we report a microwave phase shifter of the coplanar waveguide with float electrodes using ferro-electric liquid crystal and discuss its fast switching response.

EXPERIMENTS

Figure 1 shows a schematic of the device construction used in this study. Two polytetraflouroethylene (PTFE) substrates with a thickness of 40 μm for high-frequency circuits were used in this study. A coplanar waveguide, whose center conductor is 2 mm and gaps between the central conductor and two ground planes are 100 μm, was constructed on the lower PTFE substrate. The upper PTFE substrate, which has an electrode with a width of 300 μm for applying dc voltage to the liquid crystal, was fixed on the substrate of the

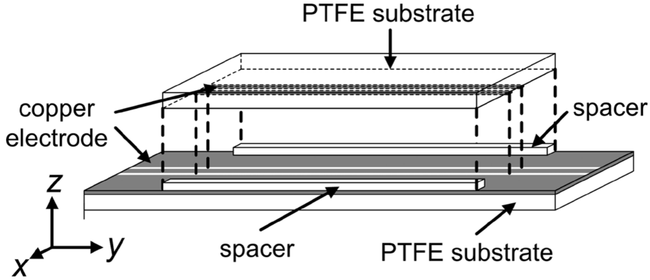

FIGURE 1 Schematic of device structure used in this study.

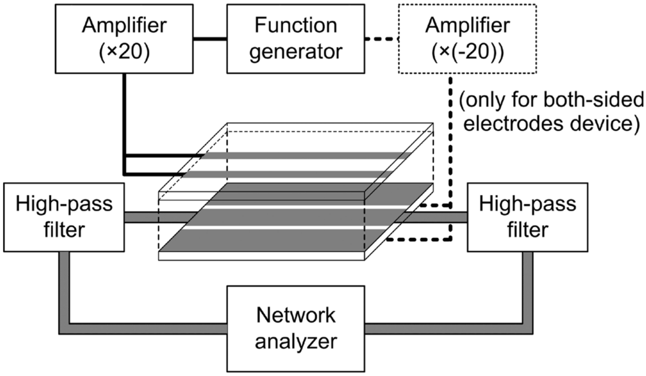

FIGURE 2 Experimental setup used in this study.

coplanar waveguide with spacers. Two types of devices were used in this study. One device had two electrodes on the bottom sides of the upper and lower PTFE substrates for applying dc voltage to the liquid crystal and is denoted as the both-sided-electrode device in this paper. The other device had only one electrode on the bottom side of the upper PTFE substrate and is denoted as the one-sided-electrode device. The length of the coplanar waveguide was 20 mm, and the thickness of the liquid crystal layer was 50 μm. Both surfaces of the PTFE substrates, which were in contact with the liquid crystal, were coated with polyimide (JSR, AL1254) and rubbed for unidirectional alignment. The rubbing direction was at an angle of 45° from the propagation direction of microwaves. The ferroelectric liquid crystal material used in this study was FELIX-015/000 (AZ Electronic Materials), which has a tilt angle of 22° in 25°C.

Figure 2 shows a schematic of the experimental setup used in this study. The coplanar waveguide device was incorporated in two high-pass filters. In this device construction, the high-pass filters were not essentially needed because a high dc voltage is not applied to the center conductor. The dc voltage was applied to the liquid crystal using a function generator (Tektronix, AFG310) and a power amplifier (Toyo, A400DI). The propagation phase shift of the microwave was measured using vector network analyzers (Anritsu, 37369 C and Agilent, E8363B) in the frequency range from 10 GHz to 30 GHz. All measurements were executed at 25°C, at which the liquid crystal shows the Sm C* phase.

RESULTS AND DISCUSSION

Figure 3 shows frequency dependences of measured insertion losses of the microwave in the both-sided-electrode and one-sided-electrode

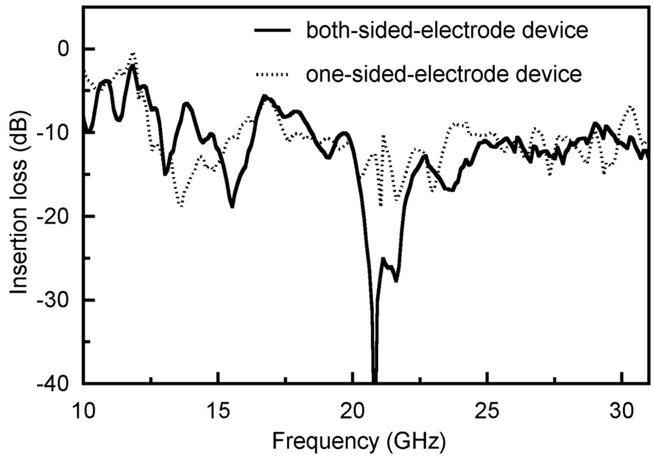

FIGURE 3 Frequency dependences of measured insertion losses of microwave in two types of devices.

devices. The insertion losses of both devices are around 10 dB except at some frequencies and are rather high. The insertion losses are almost the same in the two devices, and therefore, the effect of the electrodes when applying the dc voltage to the liquid crystal can be ignored. We measured the phase shift while applying the dc voltage to the liquid crystal at several frequencies, in which the insertion losses are relatively small.

In the coplanar waveguide, the microwave propagates in the center conductor along the y-axis shown in Figure 1 while the electric field is irradiated along the x-axis. Therefore, the microwave is affected by the dielectric permittivity along the x-axis. Figure 4 shows a schematic of the molecular orientation of the ferroelectric liquid crystal under the application of the dc voltage to the liquid crystal. In this study, the rubbing direction is at 45° from the propagation direction, and the tilt angle of the ferroelectric liquid crystal is 22°. Therefore, the angle between the molecular direction of the ferroelectric liquid crystal and the electric field direction of the microwave changes from 23° to the 67°. Consequently, the dielectric permittivity along the electric field direction of the microwave is changed by the application of the dc voltage to the ferroelectric liquid crystal and the phase shift of the microwave.

Figure 5 shows the microwave frequency dependences of the phase shift of the microwave in both devices. The phase shifts in both devices were proportional to the frequency of the microwave, and the phase

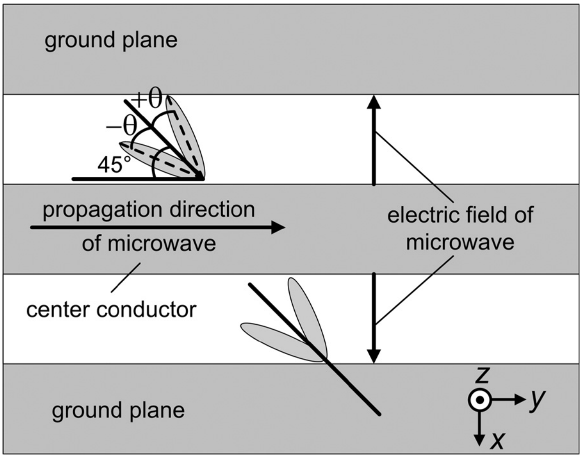

FIGURE 4 Schematic of molecular orientation of ferroelectric liquid crystal under application of dc voltage.

shift of the both-sided-electrode device was higher than that of the one-sided-electrode device. The phase shift $\Delta\phi$ is given by the following equation:

$$\frac{\Delta\phi}{360^\circ} = l\frac{f}{c}\left(\sqrt{\varepsilon_{+,eff}} - \sqrt{\varepsilon_{-,eff}}\right) \tag{1}$$

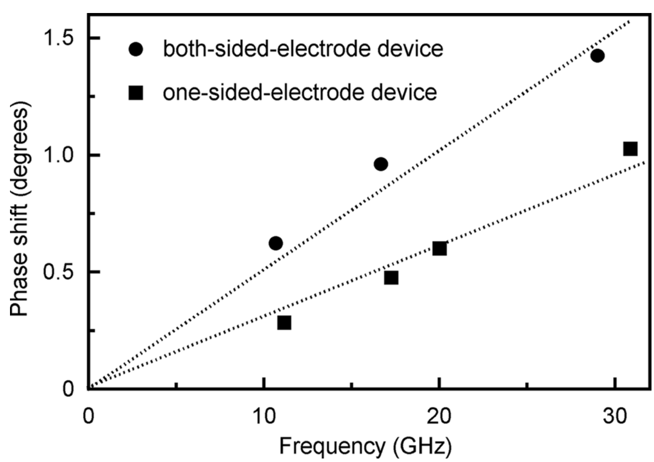

FIGURE 5 Frequency dependences of measured phase shift of microwave in two types of devices.

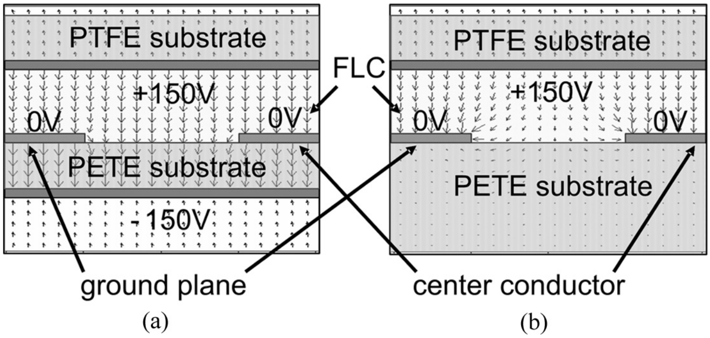

FIGURE 6 Calculated electric field distributions in (a) both-sided-electrode device and (b) one-sided-electrode device.

$$\varepsilon_{+,eff} = \frac{\varepsilon_+ + \varepsilon_r}{2}, \quad \varepsilon_{-,eff} = \frac{\varepsilon_- + \varepsilon_r}{2}, \tag{2}$$

where l is the length of the coplanar waveguide, f is the frequency of the microwave, c is the speed of light in vacuum, ε_r is the dielectric permittivity of the PTFE substrate, and ε_+ and ε_- are the dielectric permittivities along the x-axis under the application of positive and negative voltages, respectively. From Eq. (1), the phase shift is proportional to the frequency of the microwave if the dielectric permittivity difference does not have any frequency dependence. The phase shift of the both-sided-electrode device was larger than that of the one-side-electrode device. To clarify the difference in the phase shift between the two devices, the distributions of the electric fields applied to the liquid crystal in them were calculated. Figure 6 shows the distributions of the electric fields applied to the liquid crystal in the two devices when a dc voltage of 150 V was applied to the upper electrode in both devices and an additional voltage of −150 V was applied to the lower electrode in the both-sided-electrode device. In this calculation, the voltage of the center conductor was defined as zero because it is negligible compared with the ±150 V at the upper and lower electrodes. In this Figure, the electric field distributions are shown around one of two gaps between the center conductor and the ground planes of the coplanar waveguide. The electric field distribution in the liquid crystal layer of the both-sided-electrode device was uniform, as shown in Figure 6(a). On the other hand, the electric field distribution in the one-sided-electrode device was not uniform in the gap area between the center conductor and the ground plane, as shown in Figure 6(b). In particular the electric field in the region near the lower PTFE

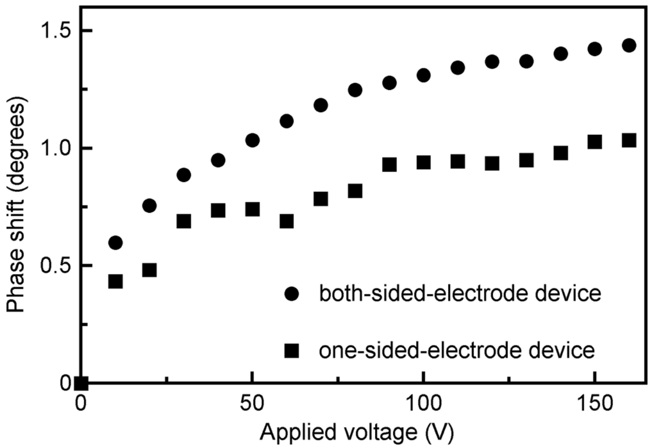

FIGURE 7 Voltage dependences of measured phase shifts in two types of devices at the microwave frequency of 29 GHz.

substrate is very small, and thus, the ferroelectric liquid crystal molecules in this region cannot respond. Therefore, it is considered that the phase shift in the one-sided-electrode device was smaller than that in the both-sided-electrode device.

Figure 7 shows the applied voltage dependences of the measured phase shifts of the both-sided-electrode and one-side-electrode devices at a microwave frequency of 29 GHz, when a square voltage with a frequency of 0.5 Hz was applied to the liquid crystal layer. The phase shifts increased with applied voltage in both devices, and the phase shift in the both-sided-electrode device was larger than that in the one-side-electrode device. From this Figure, it is confirmed that the variable phase shifter was realized. Figure 8 shows the applied voltage dependences of the measured response times in both devices at the microwave frequency of 29 GHz In this measurement, the rise time and decay time are defined as the response times when the applied voltage changes from the positive to the negative and from the negative to the positive, respectively. All response times decreased with increasing applied voltage, and the rise and decay times of the both-sided-electrode device are shorter than those of the one-sided-electrode device, as shown in this Figure. The longer response time in the one-sided-electrode device is caused by the application of a lower electric field to the liquid crystal in the gap region near the lower PTFE substrate, as shown in Figure 6. In other words, the region in which the ferroelectric liquid crystal molecules do not respond completely causes the response time to increase. Note in Figure 8 that the rise and decay times of the both-sided-electrode device above 120 V were

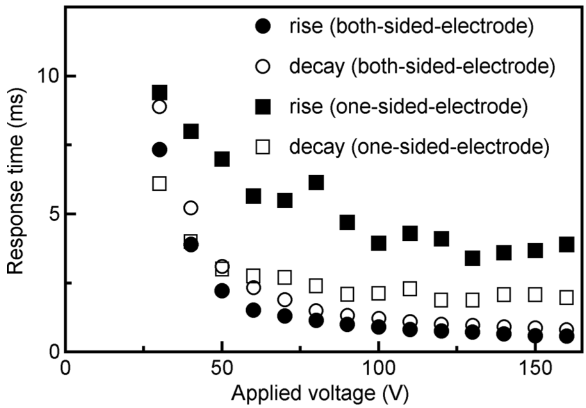

FIGURE 8 Voltage dependences of rise and decay times in two types of devices at the microwave frequency of 29 GHz.

both shorter than 1 ms. From this result, it was confirmed that a very high speed variable phase shifter was realized and that the coplanar waveguide with float electrodes using ferroelectric liquid crystal can be adopted for high-speed phase shifters.

CONCLUSIONS

Two types of microwave variable phase shifters of a coplanar waveguide with float electrodes on both sides and a float electrode on one side using ferroelectric liquid crystal were discussed. The measured phase shift was proportional to the frequency of the microwave, and the phase in the both-sided-electrode device was larger than that in the one-sided-electrode device. An incomplete electric field in the liquid crystal region between the center conductor and the ground plane near the lower substrate was confirmed in the one-side-electrode device by calculating the electric field distribution. The measured phase shift increased with increasing applied voltage in both devices. The response time of the both-sided-electrode device was less than 1 ms above 120 V, and a very high speed variable phase shifter was realized. The coplanar waveguide with a float electrode using ferroelectric liquid crystal is promising for microwave phase shifter application.

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