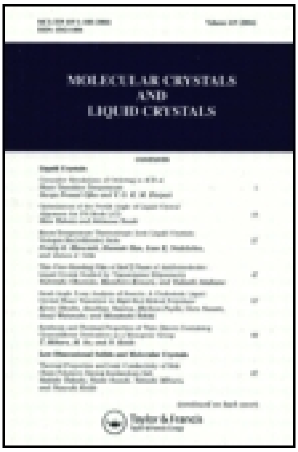

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Effective Dielectric Permittivity of Coplanar Waveguide Type Microwave Phase Shifter Using Ferroelectric Liquid Crystal

H. Moritake [a] , R. Ozaki [a] , T. Kamei [b] & Y. Utsumi [b]
[a] Department of Electrical and Electronic Engineering, National Defense Academy, Hashirimizu, Yokosuka, Kanagawa, Japan
[b] Department of Communications Engineering, National Defense Academy, Hashirimizu, Yokosuka, Kanagawa, Japan

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Effective Dielectric Permittivity of Coplanar Waveguide Type Microwave Phase Shifter Using Ferroelectric Liquid Crystal

H. MORITAKE,[1] R. OZAKI,[1] T. KAMEI,[2] AND Y. UTSUMI[2]

[1]Department of Electrical and Electronic Engineering, National Defense Academy, Hashirimizu, Yokosuka, Kanagawa, Japan
[2]Department of Communications Engineering, National Defense Academy, Hashirimizu, Yokosuka, Kanagawa, Japan

A coplanar waveguide type microwave phase shifter using ferroelectric liquid crystal is constructed and its fundamental characteristics are measured. An analysis procedure of the effective permittivity of the phase shifter is explained. The decrease of the width of the center conductor in the phase shifter leads the increase of the dielectric permittivity change, consequently increasing the phase shift. The distance between the center conductor and ground plane needs the same as the width of the center conductor. Furthermore, it is confirmed that the arrangement of the dielectric substrate instead of the liquid crystal layer is useful technique.

Keywords Coplanar waveguide; effective permittivity; ferroelectric liquid crystal; microwave phase shifter; variable delay line

1. Introduction

For increasing use of mobile communications, satellite broadcasting and intelligent transport systems, electrically-controllable microwave components such as phase shifter and attenuator have attracted considerable attention. Liquid crystals have a large dielectric anisotropy in the microwave region and it is easy to control the dielectric permittivity by applying an electric field to the liquid crystal. Therefore, microwave applications using nematic liquid crystals have been reported [1–4]. Among them, a microstrip line structure has been mainly used in their applications, but there are large problems about the response time upon voltage removal. For the improvement of the response time, the use of a coplanar waveguide with a floating electrode for the microwave phase shifter has been proposed [5]. The response time of this type becomes shorter than that of the microstrip line type, because the molecular reorientation of the liquid crystal in the coplanar waveguide type is controlled by the direction change of the electric field which is always applied. The response

Address correspondence to H. Moritake, Department of Electrical and Electronic Engineering, National Defense Academy, 1-10-20 Hashirimizu, Yokosuka, Kanagawa 239-8686, Japan. Tel.: +81-468413810 ext. 3341; Fax: +81-4684445903; E-mail: moritake@nda.ac.jp

time at the present moment is about a hundred millisecond [6] and it is not sufficient for the application which is required the dynamic response.

On the other hand, ferroelectric liquid crystals have a spontaneous polarization and show a high response speed [7]. A microwave variable phase shifter using ferroelectric liquid crystal was firstly reported utilizing a microstrip line structure [8,9]. In this case, the response time is, of course, shorter than that in the case using the nematic liquid crystal, however, it is not sufficiently short because the origin of the response is unwinding and winding of a helical structure and the spontaneous polarization is not effectively utilized. To improve the response time, we have studied the microwave phase shifter of the coplanar waveguide with floating electrodes using ferroelectric liquid crystal and its fast switching time with a millisecond order has been reported [10–12]. The problem in this case is very small phase shift value and the increase of it is expected. For the improvement, it is expected that the relation between the effective dielectric permittivity of the microwave phase shifter and its structure is clarified. In this paper, we firstly explain an analysis procedure of the effective permittivity of the coplanar waveguide type microwave phase shifter using ferroelectric liquid crystal and then the relation between the effective permittivity change and the device structure of the phase shifter is discussed.

2. Experimental Procedure

Figure 1 shows a schematic of the device structure used in this study. A poly(tetraflouroethylene) (PTFE)-glass substrate (Nippon Pillar Packing, NPC-F260A) with a thickness of 40 μm was used as the dielectric substrate for the high frequency circuit. A coplanar waveguide, whose center conductor is 250 μm in width and gaps between the central conductor and two ground planes are 20 μm in width, was constructed on the dielectric substrate with a thickness of 80 μm. Another dielectric substrate with a thickness of 40 μm was fixed on the dielectric substrate of the coplanar waveguide with polyethylene terephthalate (PET) film with a thickness of 50 μm as spacers, and a liquid crystal cell was prepared. Two floating electrodes for the liquid crystal driving were constructed on the upper side of the upper dielectric substrate and the lower side of the lower dielectric substrate. The length of the coplanar waveguide of the liquid crystal cell was 15 mm. Both surfaces of the dielectric substrates, which were in contact with the liquid crystal, were coated with polyimide (JSR, AL1254) and were rubbed to achieve unidirectional alignment. The rubbing direction was at an angle of 45° from the propagation direction of the microwave. The liquid

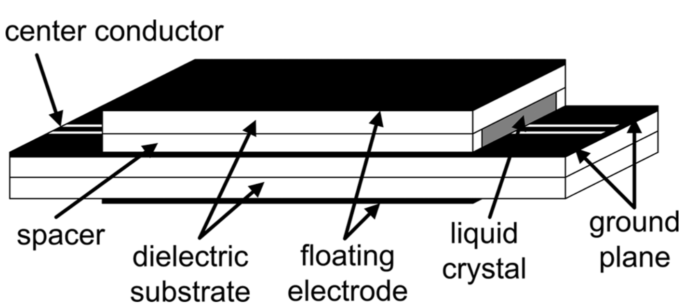

Figure 1. Schematic of device structure used in this study.

crystal material used in this study was FELIX-015/000 (AZ Electronic Materials), which has a tilt angle θ of 22° at 25°C.

The propagation loss and phase shift of the microwave were measured using a vector network analyzer (Agilent, E8363B). The dc voltage was applied to the liquid crystal using a function generator (Tektronix, AFG310) and a power amplifier (FLC, A400DI). All measurements were performed at 25°C, at which the liquid crystal shows the chiral smectic C (Sm C*) phase.

3. Analysis Procedure

In the microwave variable phase shifter, the propagation phase shift of the microwave ΔP is given by

$$\Delta P = \frac{2\pi f l}{c} \Delta\sqrt{\varepsilon_{eff}}, \tag{1}$$

where l is the length of the coplanar waveguide with the liquid crystal cell, f is the frequency of the microwave, c is the speed of light in vacuum, and $\Delta\sqrt{\varepsilon_{eff}}$ is the difference of the square root of the effective dielectric permittivities of the coplanar waveguide under the application of positive and negative voltages to the liquid crystal layer. Figure 2 shows a schematic of the liquid crystal orientations and the dielectric permittivities under the application of the bias electric fields in both polarities. In this study, the rubbing direction is at 45° from the propagation direction, as mentioned above. Therefore, the angle between the molecular direction of the liquid crystal and the electric field direction of the microwave is $45 + \theta°$ or $45 - \theta°$. The dielectric permittivities along the electric field direction of the microwave (y-axis) and perpendicular to the substrate (x-axis) are given by

$$\varepsilon_{FLC\_x} = \varepsilon_{\perp}, \tag{2}$$

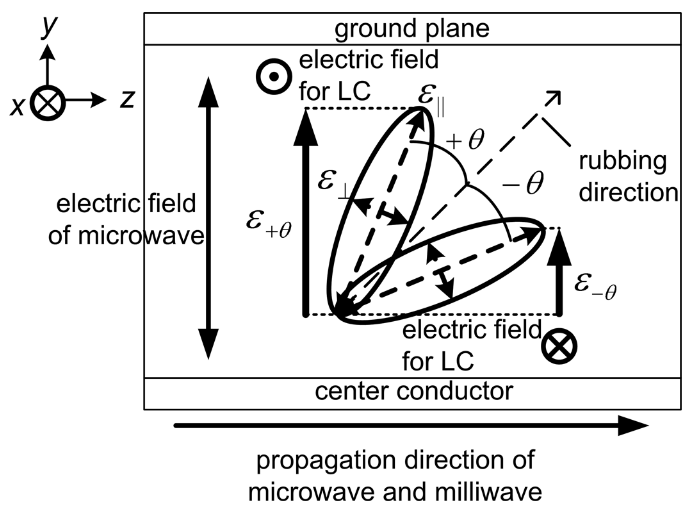

Figure 2. Schematic of liquid crystal molecular orientation and dielectric permittivities under applications of bias electric field.

$$\varepsilon_{FLC\_y,\pm} = \frac{\varepsilon_{\|}\varepsilon_{\perp}}{\varepsilon_{\|}\cos^2(45^\circ \pm \theta) + \varepsilon_{\perp}\sin^2(45^\circ \pm \theta)}, \tag{3}$$

where $\varepsilon_{||}$ and $\varepsilon_{\perp}$ are the dielectric permittivities along the director and perpendicular to it in the microwave region, respectively. In this paper, we discuss the macroscopic dielectric permittivity.

The electric field distribution of the coplanar waveguide was calculated using an electromagnetic simulator (CST, Microwave Studio). Figure 3 shows the calculation result of the electric field distribution in the same structure of the device used in the measurement. In this calculation, dielectric permittivities of the dielectric substrate and the liquid crystal are given at the same value because of simplified calculation. Figure 4 shows a cross section diagram of the coplanar waveguide used in this study. The effective dielectric permittivity is expressed by

$$\varepsilon_{eff,\pm} = \frac{\varepsilon_{sub}\int_{S1}\left(E_x^2 + E_y^2\right)dS + \int_{S2}\left(\varepsilon_{FLC\_x}E_x^2 + \varepsilon_{FLC\_y,\pm}E_y^2\right)dS}{\int_{S1+S2}\left(E_x'^2 + E_y'^2\right)dS}, \tag{4}$$

where ε_{sub} is the dielectric permittivity of the substrate, ε_{FLC_x} and $\varepsilon_{FLC\_y,\pm}$ are the dielectric permittivities of the liquid crystal shown in Eq. (2) and Eq. (3), and $S1$ and $S2$ are the areas of the dielectric substrate and liquid crystal, respectively. E' is the electric field strength under the condition of uniform dielectric medium. The phase shift is expressed by

$$\Delta P = \frac{2\pi fl}{c}\Delta\left(\sqrt{\varepsilon_{eff,+}} - \sqrt{\varepsilon_{eff,-}}\right) \tag{5}$$

using Eq. (1) and Eq. (4).

In this study, the dielectric permittivity of the dielectric substrate (ε_{sub}) was 2.60, whereas that of FLC was not clarified. The phase shift was calculated under the assumption that the dielectric permittivity perpendicular to the molecular long axis ($\varepsilon_{\perp}$) was 2.50, which is a typical value in conventional nematic liquid crystals.

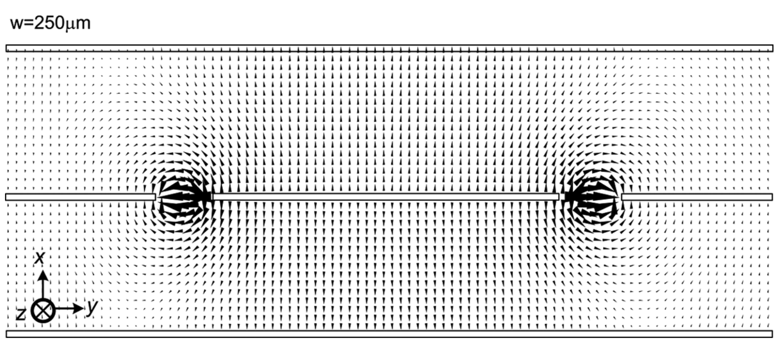

Figure 3. Calculated microwave electric field distribution of same structure of device used in this study.

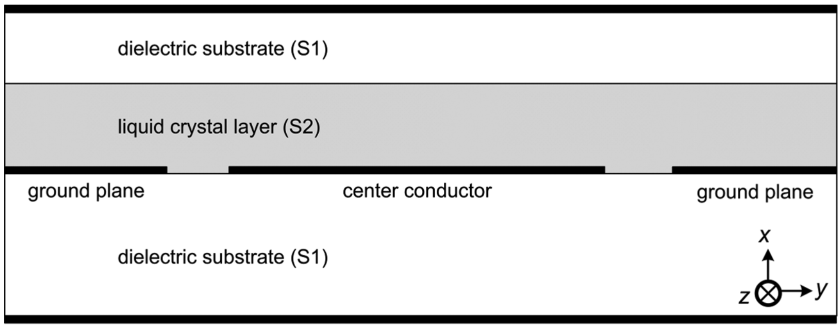

Figure 4. Cross section diagram of coplanar waveguide used in this study.

4. Results and Discussion

Figure 5 shows measured frequency dependences of the insertion loss and phase shift of the microwave under the application of the bias voltage. The insertion loss of the device increases with increasing frequency and is relatively high, therefore it is necessary to decrease it for the device application. The phase shift increases with increasing applied voltage, and is proportional to the frequency of the microwave, as shown in Figure 5(b). When the $\Delta\sqrt{\varepsilon_{eff}}$ is constant in this frequency range, the phase shift is proportional to the measured frequency, as mentioned in Eq. (1). Therefore, it was confirmed from Figure 5(b) that the dielectric anisotropy is constant in the measured frequency range.

The measured phase shift under application of 200 V was 3.2 degrees as shown in Figure 5(b). From this value of the phase shift, the anisotropy of the refractive index of the liquid crystal, $\Delta n(=\Delta\sqrt{\varepsilon_{LC}}=\sqrt{\varepsilon_{\|}}-\sqrt{\varepsilon_{\perp}})$, in the microwave region was estimated at 0.072.

The phase shift ΔP is proportional to the difference of the effective dielectric permittivities of the coplanar waveguide under the application of positive and negative

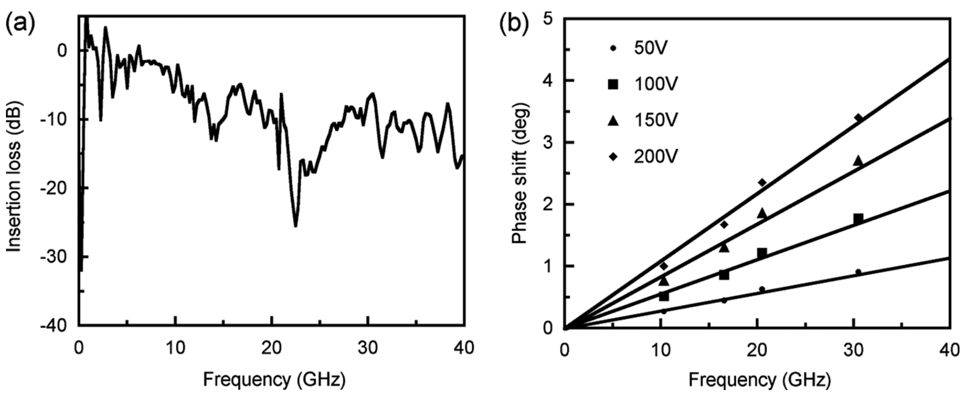

Figure 5. Frequency dependences of (a) measured insertion loss and (b) measured phase shift of microwave.

voltages to the liquid crystal layer ($\Delta\sqrt{\varepsilon_{eff}} = \sqrt{\varepsilon_{eff,+}} - \sqrt{\varepsilon_{eff,-}}$), as shown in Eq. (5). In this condition, $\Delta\sqrt{\varepsilon_{eff}}$ was estimated at 0.0060 and was very small.

To improve the $\Delta\sqrt{\varepsilon_{eff}}$ of the phase shifter, the relation between the $\Delta\sqrt{\varepsilon_{eff}}$ and the device structure was studied. Firstly, the width of the center conductor, *w*, was changed. Figure 6 shows calculated results of the electric distributions in the same structure except the width of the center conductor. The $\Delta\sqrt{\varepsilon_{eff}}$ was calculated from the electric distribution shown in Figure 6 and Eq. (4). Figure 7 shows the $\Delta\sqrt{\varepsilon_{eff}}$ as a function of the width of the center conductor. The $\Delta\sqrt{\varepsilon_{eff}}$ increases with decreasing the width of the center conductor. The influence of the electric field from the center conductor to the floating electrodes decreases with decreasing the width of the center conductor, as shown in Figure 3 and Figure 6. Therefore, it is considered that the $\Delta\sqrt{\varepsilon_{eff}}$ increases with decreasing the width of the center conductor. The $\Delta\sqrt{\varepsilon_{eff}}$ is in the condition of 50 μm in the width of the center conductor is 1.6 times as large as that in the condition of 250 μm in the width. This fact leads that the decrease of the width of the center conductor is useful to increase the $\Delta\sqrt{\varepsilon_{eff}}$.

Figure 8 shows calculated $\Delta\sqrt{\varepsilon_{eff}}$ as a function of the distance *d* between the center conductor plane and the floating electrodes where the thickness of liquid crystal layer is 50 μm and the width of the center conductor is 150 μm. The $\Delta\sqrt{\varepsilon_{eff}}$ increases with increasing the distance *d* though the liquid crystal layer is fixed at 50 μm. When the distance *d* increases, the electric field from the center conductor to the floating electrode decreases and the electric field from the center conductor to the ground plane. Therefore, the y-component of the electric field in the liquid crystal layer

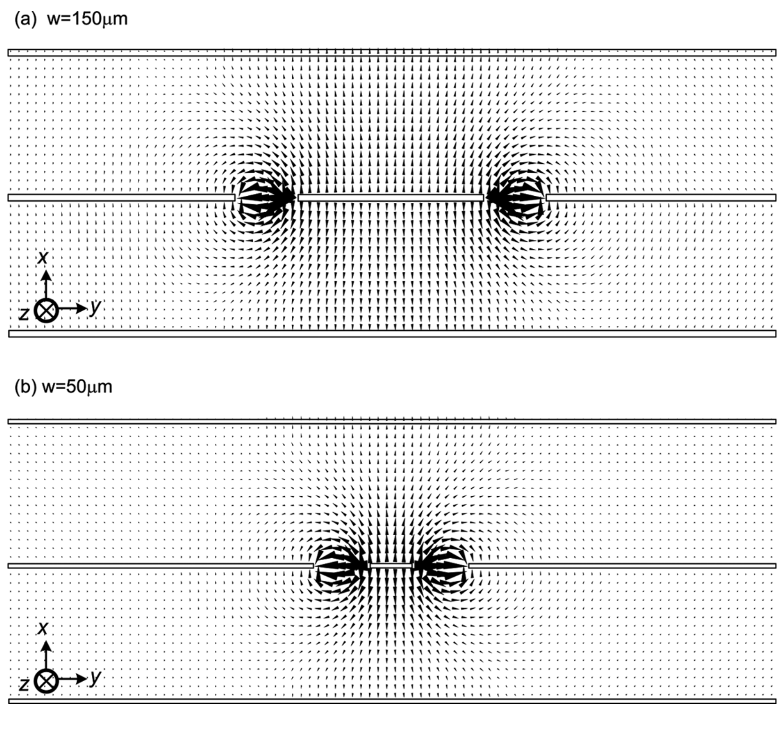

Figure 6. Calculated microwave electric field distribution at conditions of (a) 150 μm and (b) 50 μm in width of center conductor.

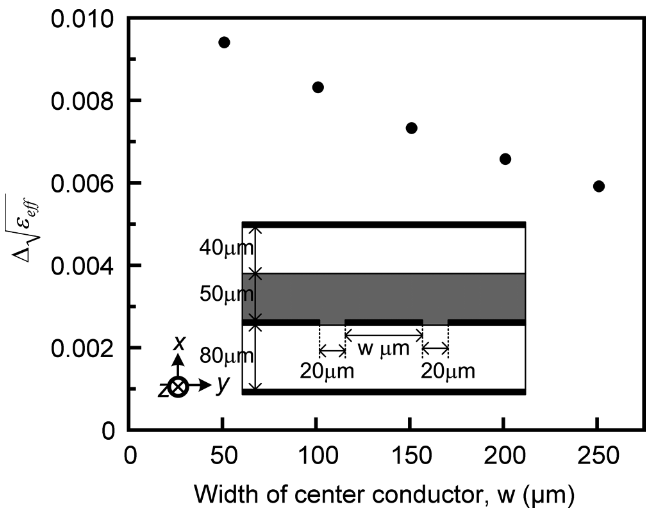

Figure 7. Difference of square root of effective dielectric permittivities as a function of width w of center conductor.

increases, and consequently the $\Delta\sqrt{\varepsilon_{eff}}$ increases. As shown in Figure 8, the $\Delta\sqrt{\varepsilon_{eff}}$ is almost saturated above the distance d of 150 μm which is the same the width of the center conductor. From this result, we obtained a design guideline of the device in relation between the width of the center conductor and the distance d.

Figure 9 shows the calculated $\Delta\sqrt{\varepsilon_{eff}}$ as a function of the liquid crystal layer thickness d_{LC}. The $\Delta\sqrt{\varepsilon_{eff}}$ increases with increasing the d_{LC} and is saturated above 50 μm. In this case, the gaps between the center conductor and the ground planes are 20 μm and the electric field from the center conductor to the ground plane

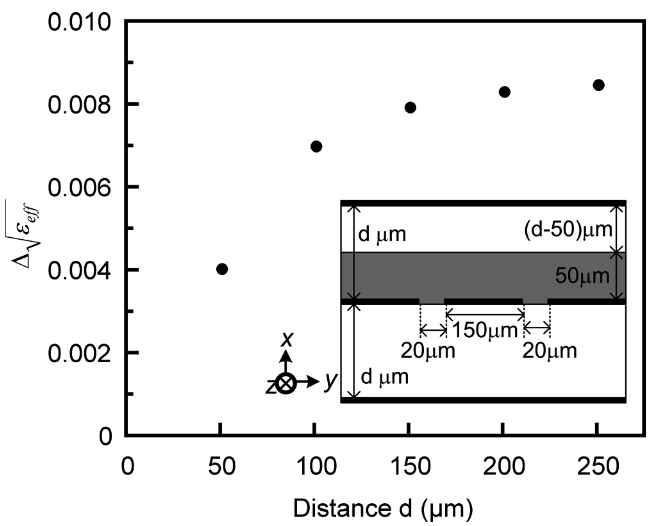

Figure 8. Difference of square root of effective dielectric permittivities as a function of distance d between center conductor plane and floating electrodes.

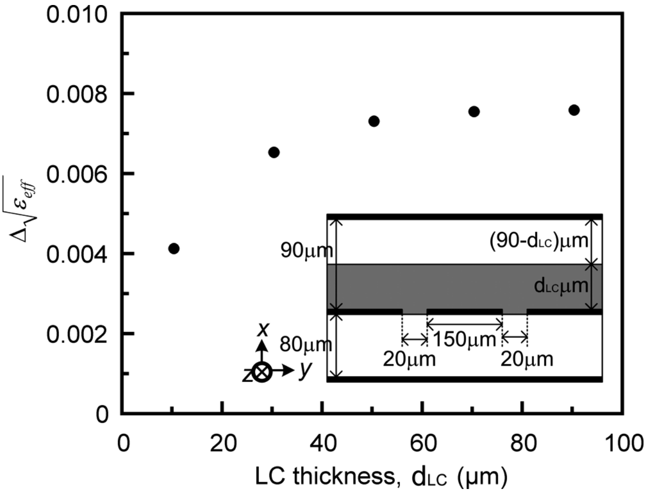

Figure 9. Difference of square root of effective dielectric permittivities as a function of thickness of liquid crystal layer.

converges near the gap areas, as shown in Figure 6(a). Therefore, the thickness of the liquid crystal layer is sufficient as two or three times of the gap width. It general, the achievement of the unidirectional alignment in thick cell of ferroelectric liquid crystals is more difficult than that of nematic liquid crystals. So, it is confirmed that the use of the dielectric substrate instead of the ferroelectric liquid crystal below the upper floating electrode is useful technique.

5. Conclusions

A coplanar waveguide type microwave phase shifter using ferroelectric liquid crystal was constructed and its fundamental characteristics were measured. An analysis procedure of the effective permittivity of the phase shifter was explained. From this analysis, the decrease of the width of the center conductor in the phase shifter conducted the increase of the dielectric permittivity change, consequently increasing the phase shift. We clarified that the distance between the center conductor and ground planes needs the same as the width of the center conductor. Furthermore, it was confirmed that the arrangement of the dielectric substrate instead of the liquid crystal layer was useful technique. The present analysis method is promising for designing the coplanar waveguide type microwave phase shifter using ferroelectric liquid crystal.

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