Microwave Variable Delay Line Using Dual-Frequency Switching-Mode Liquid Crystal

Takao Kuki, *Member, IEEE*, Hideo Fujikake, and Toshihiro Nomoto, *Member, IEEE*

***Abstract*—A method was investigated to reduce the insertion loss and response time in the phase shift in a microwave variable delay line using liquid crystal (LC). In variable delay lines using conventional nematic LC, reducing the insertion loss conflicts with reducing the phase-shift response-time dependence on the thickness of the LC layer; thus, it is very difficult to simultaneously satisfy both requirements. Here, the use of dual-frequency switching-mode liquid crystal (DFSM LC) for the variable delay line is demonstrated as one approach to solving this problem. By using the characteristics of DFSM LC, in that the alignment of the LC can be controlled with a control voltage and its frequency, it becomes possible to control the LC alignment to be in an always electrically driven condition by applying a combination of control voltages of dc and several kilohertz. Experimental results of a microwave variable delay line using DFSM LC show that it is possible to reduce both the phase-shift response time and insertion loss.**

***Index Terms*—Dual-frequency switching-mode liquid crystal (DFSM LC), insertion loss, microwave, phase-shift decay time, variable delay line.**

I. Introduction

MICROWAVE device technologies that can electronically vary the amplitude, phase, or frequency of a microwave signal have been the target of recent investigations. For example, there has been research on variable delay lines [1], variable oscillators [2], and other such devices that use the magnetostatic mode. Lately, a variable resonator [3] and variable phase shifter [4], [5], which use a change in the dielectric characteristic of ferroelectric materials by changing an external bias voltage, have been reported. It has been explained that the amplitude, phase, and other transmission characteristics of a microwave can be controlled by using an external signal to control the permittivity of the dielectric material and/or the permeability of the magnetic material in microwave and millimeter-wave transmission lines. In the case of a microstrip line, the microwave transmission characteristics of phase, amplitude, etc., are controlled by changing the permittivity of the dielectric substrate used for the microstrip line.

Liquid crystal (LC) has drawn attention because its permittivity can be changed, thus making it attractive for use as a dielectric substrate material for microstrip lines. The molecules of LC can change their alignment by changing an external bias electrical field, and it is known that the permittivity of LC also changes in accord with the LC alignment [6]. By using this phenomenon, researchers have endeavored to invent a device in which the transmission characteristics of a microwave and millimeter-wave transmission line can be controlled externally. Lim *et al.* reported a millimeter-wave variable phase shifter in which a waveguide is filled with nematic LC and the LC is controlled using voltage [7]. Dolfi *et al.* reported a broad-band variable phase shifter in the microwave and millimeter-wave band that uses nematic LC for the dielectric substrate of a microstrip line [8], [9].

We are researching devices to control microwaves using LC [10]–[12], and have investigated reducing the insertion loss in microwave variable delay lines by using LC. The experimental results previously reported for microstrip-line-type variable delay lines based on the conventional nematic LC were as follows.

- Insertion loss, which is too large for practical use, was dominated by the conductor loss of the strip conductor.
- The large conductor loss was caused by the narrow width of the strip conductor of the microstrip line. The narrowness of the strip conductor was the result of the thinness of the LC layer fabricated to keep the characteristic impedance constant.
- To reduce the conductor loss, it was necessary to make the LC layer thicker and the strip conductor wider.
- However, a thicker LC layer caused the slow phase-shift response time in accord with a change in the control voltage.

In other words, reducing the phase-shift response time and lowering the insertion-loss characteristics have mutually contrary requirements with respect to the LC layer thickness; hence, those requirements have not been satisfied simultaneously for the variable delay lines that use conventional nematic LC [10].

We newly intend to improve the phase-shift response time and insertion loss by using the dual-frequency switching-mode liquid crystal (DFSM LC), which is known to have a fast response time when used in a display device [13].

First, the principle of DFSM LC driven by two frequencies is explained. Second, the design and fabrication of a DFSM-LC microwave variable delay line is described and the results of an evaluation of its phase characteristics, insertion loss, and phase-shift response time is reported. An evaluation of the phase-shift response time of the LC variable delay line has not previously been reported. Third, the evaluation method is defined. Finally,

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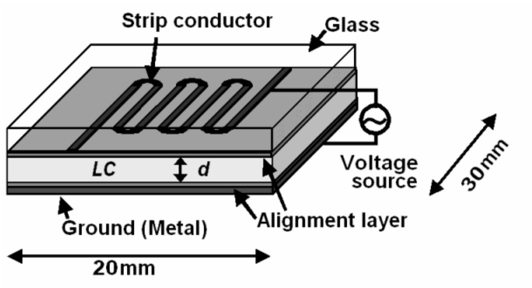

Fig. 1. Structure of the variable delay line using LC.

it is demonstrated that the experimental variable delay line can reduce insertion loss without increasing the phase-shift response time.

II. Application of a DFSM LC to Variable Delay Lines

A. LC Alignment and Variable Delay-Line Operation

The structure of a microwave variable delay line that uses LC [8]–[10] is shown in Fig. 1. If the space between the ground metal and glass is filled with LC, one can construct a microstrip line for which the LC layer acts as a dielectric-substrate material. Also, by applying a control voltage between the strip conductor and ground metal, one can control the LC alignment, i.e., the permittivity, and thereby change the transmission characteristics of the microstrip line, including the delay time. In that case, the LC alignment is controlled by the torque caused by the control voltage and alignment layers.

The alignment of the conventional nematic LC used in the studies previously reported was determined by a balance between the torque due to the alignment layers and torque due to the control voltage. The magnitude of the control voltage ultimately determines the LC alignment because the torque due to the alignment layers never changes. Therefore, the result of applying a sufficiently large control voltage to LC is to align the LC along the electric field due to the control voltage. This LC alignment is nearly parallel to the microwave electric field because the transmission mode of the microstrip line is quasi-TEM. On the other hand, if the control voltage is removed (changed to 0 V), the LC becomes aligned in the direction determined by the alignment layers, which is perpendicular to the microwave electric field.

The LC layer thickness d of the conventional variable delay line shown in Fig. 1 was set to 50 μm. Considering that the thickness of the LC layer of ordinary LC display devices is several micrometers, this was a very thick LC layer. However, the thick LC layer, which reduces the insertion loss, caused the following problems. The LC alignment response time in accord with the change in the control voltage increases if the LC layer is made thicker. This results in an increase in the phase-shift response time of the variable delay line. The "rise time," which is one of the two factors in the phase-shift response time, for existence of the control voltage, is an effect of the LC realignment by the torque of the control voltage and, thus, in this electronically driven condition, is not degraded too much, even if the LC layer is thicker. The other factor is the "fall time" for removal of the control voltage; however, it is involved in the realignment

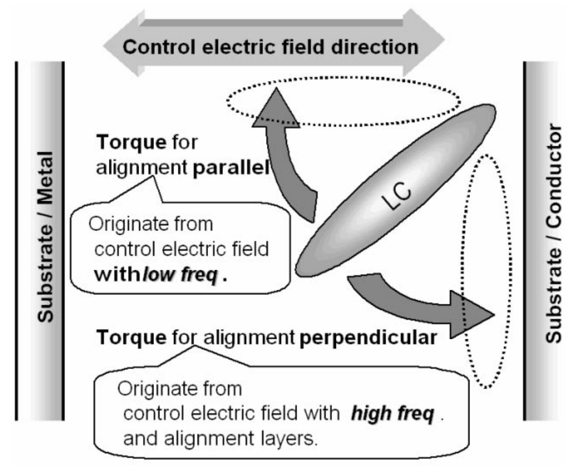

Fig. 2. Schematic showing how the DFSM LC can be aligned fast.

through the static torque of the alignment layers. This factor is known to increase in proportion to the square of the LC layer thickness [6] and, therefore, suffers a large degradation due to the increased layer thickness. A method for reducing this "fall time" is described later in this paper.

B. Principle of the Application of DFSM LC

In DFSM LC, the direction of the torque that orients the LC alignment is varied by the frequency of the control voltage, as shown in Fig. 2. When the control voltage is in the low-frequency region near dc, the torque works to align the LC molecules parallel to the direction of the electric field produced by the control voltage. When it is in the higher frequency region of several kilohertz, the torque works to align the molecules perpendicular to the field. If alignment layers are used in the conventional variable delay lines, the direction of the LC alignment can be determined by balancing the torque of the low-frequency control voltage and the sum of the torques induced by the alignment layers and high-frequency control voltage. By using control voltages whose frequencies are either above or below a crossover frequency, the LC alignment can be controlled in the same way as that used for the conventional LC. The crossover frequency is that point where the direction of the orienting torque changes from that parallel to the controlling electric field to the direction perpendicular to the field at that frequency.

That is to say, the alignment of DFSM LC becomes consistently controllable by using voltages having different frequencies. As a result, the "fall time" degradation can be made small, even for thick LC layers. Therefore, the application of a DFSM LC to variable delay lines promises to reduce insertion loss without increasing the phase-shift response time.

III. Experiments With Variable Delay Lines Using DFSM LC

A. Design and Fabrication

An experimental microstrip-line-type variable delay line using DFSM LC was designed and fabricated. The structure of the device is shown in Fig. 1 and the design parameters are listed in Table I. Two LC layer thickness values (d) of 50 and

TABLE I
DESIGN PARAMETERS OF THE LC MICROWAVE VARIABLE DELAY LINE

LC layer	Thickness(d)	50 μm / 200 μm
	$\varepsilon_{r\,(LC)}$	3.0
	$\tan\delta$	0.01
Glass substrate	Thickness	525 μm
	$\varepsilon_{r\,(Glass)}$	3.77
	$\tan\delta$	negligible
Strip conductor	Thickness	1 μm
	Width	100 μm (d= 50 μm) 410 μm (d=200 μm)
	Resistivity	2.44×10^{-8} Ωm

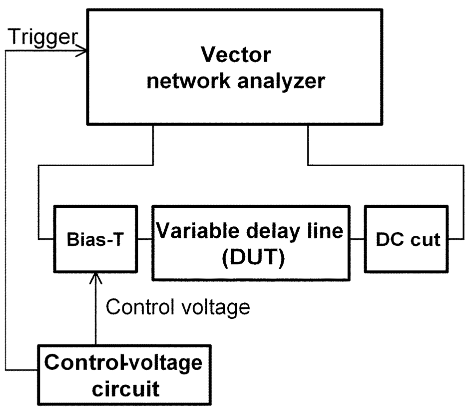

Fig. 3. Measurement setup for characteristic evaluation.

200 μm, were used, and the characteristic impedance of the transmission line was 50 Ω. The widths of the respective strip conductors were 100 μm for the 50-μm-thick layer and 410 μm for the 200-μm-thick layer. The strip conductor was formed by the deposition of a metal thin film on the glass. The line length was 193 mm. The direction of the initial alignment of the LC was set to the microwave propagation direction. The crossover frequency of the DFSM-LC material (JB-F003) used here was approximately 3 kHz. In conventional LC variable delay lines [10], the structure and design parameters are the same as those presented in Fig. 1 and Table I; however, only the 50-μm-thick LC layer is considered in this paper.

B. Method of Evaluating Characteristics and Measurement Results

The fabricated variable delay line was examined by measuring the phase-shift characteristics for changes of the control voltage, insertion loss, and phase-shift response time for the control voltage. The measurement setup for evaluating the characteristics is shown in Fig. 3. The control-voltage circuit can supply various waveforms for the above characteristic measurements. The control voltage is superimposed on the microwave by the bias-T and applied to the variable delay line. The phase shift and insertion loss are measured by the vector network analyzer.

1) Phase-Shift Characteristic: The phase-shift characteristic was measured for the variable delay line with the 200-μm-thick DFSM-LC layer. The measurement frequency

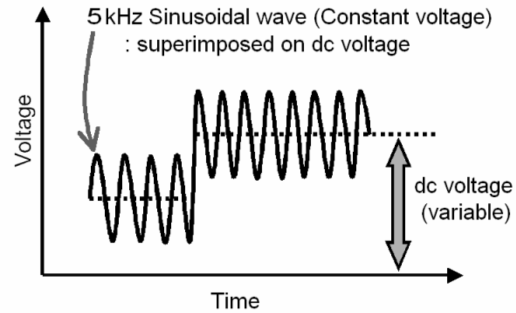

Fig. 4. Control voltage waveform for the variable delay line using DFSM LC.

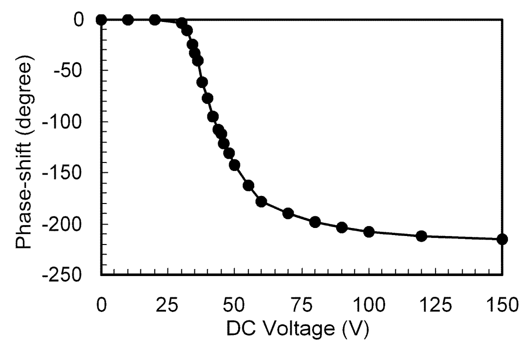

Fig. 5. Phase-shift characteristic of the variable delay line for different dc control voltages (measured at 10 GHz).

was 10 GHz. The control-voltage waveform for the DFSM LC is shown in Fig. 4. A dc voltage, which was lower than the crossover frequency, was chosen for the voltage orienting the LC in the direction of the microwave electric field, and a 5-kHz sinusoidal wave, which was higher than the crossover frequency, set the LC alignment perpendicular to the microwave electric-field direction. The control voltage was formed from the sum of those two voltages.

First, the 5-kHz sinusoidal wave was fixed at 100-V peak-to-peak (pp) and the phase shift was adjusted by varying the magnitude of the dc voltage. The results of the measurements are shown in Fig. 5. By varying the dc voltage from 0 to 150 V, a 215° phase shift was achieved. This result shows a larger phase shift than that of the conventional LC variable delay line described in [10]. One reason for the large phase shift is thought to be that the LC material used here has a greater anisotropy in the permittivity. In the experiments, the detailed dielectric characteristics of the LC were not measured; however, those measurements might be required in a future investigation.

Fig. 6 shows the frequency characteristic of the phase shift for a dc control voltage of 150 V and a 5-kHz sinusoidal wave of 100 V_{pp}. The phase shift is nearly proportional to the input microwave frequency, thus, it linearly increases with an increase of the frequency except for some small ripples in the higher frequency range. These small ripples might have been caused by reflection due to an impedance mismatch between the variable delay line and measurement system. These results show that the variable delay line has a nondispersive delay characteristic over a wide microwave-frequency range.

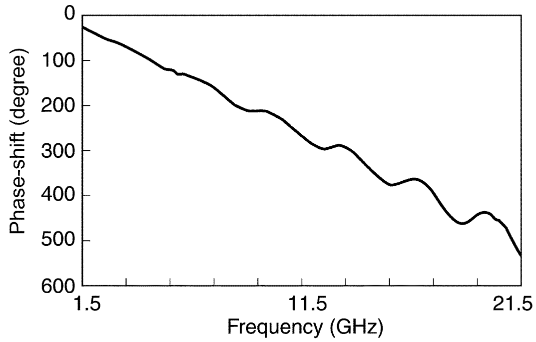

Fig. 6. Phase shift for different frequencies measured at a control voltage of 150-V dc.

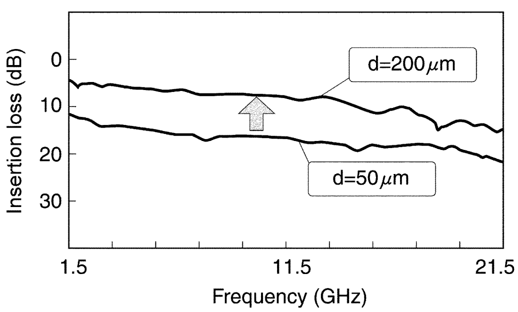

Fig. 7. Insertion-loss characteristics of the variable delay lines as a function of the LC layer thickness.

2) Insertion Loss: Fig. 7 shows the insertion-loss characteristics of the DFSM-LC variable delay line. The applied control voltage in this case was a dc voltage that was sufficient to saturate the change in the phase shift. Making the LC layer thicker reduced the insertion loss over the whole frequency range. The insertion loss was 16 dB for the 50-μm-thick LC and 7 dB for the 200-μm-thick LC at 10 GHz with good impedance matching. Improvement of the insertion loss was approximately 9 dB. From the results of electromagnetic-field simulations using the moment method, the insertion loss calculated by using the design parameters listed in Table I and taking into account additional losses, such as connector loss, [10], was 15 dB for the thickness of 50 μm and 8 dB for the thickness of 200 μm. These values are in quite good agreement with the experimental values. Thus, it has been demonstrated that it is possible to reduce the insertion loss in the fabricated variable delay lines by making the LC layer thicker and the strip conductor wider.

3) Phase-Shift Response Time: Using the measurement setup shown in Fig. 3, a transient response in the phase shift was measured when a pulsed control voltage, as shown in Fig. 8(a), was applied to the variable delay line. Since the change in the control voltage changes the LC alignment from parallel to the microwave field to perpendicular to it, the phase-shift decay time, which has been explained as the "fall time" in Section II, is evaluated. Here, the phase-shift decay time is defined as the time it takes for the phase shift to be reduced to 10% of the initial value. The measurement frequency used in this experiment was 5 GHz because the delay characteristics of the LC variable delay line are nondispersive over the microwave-frequency range.

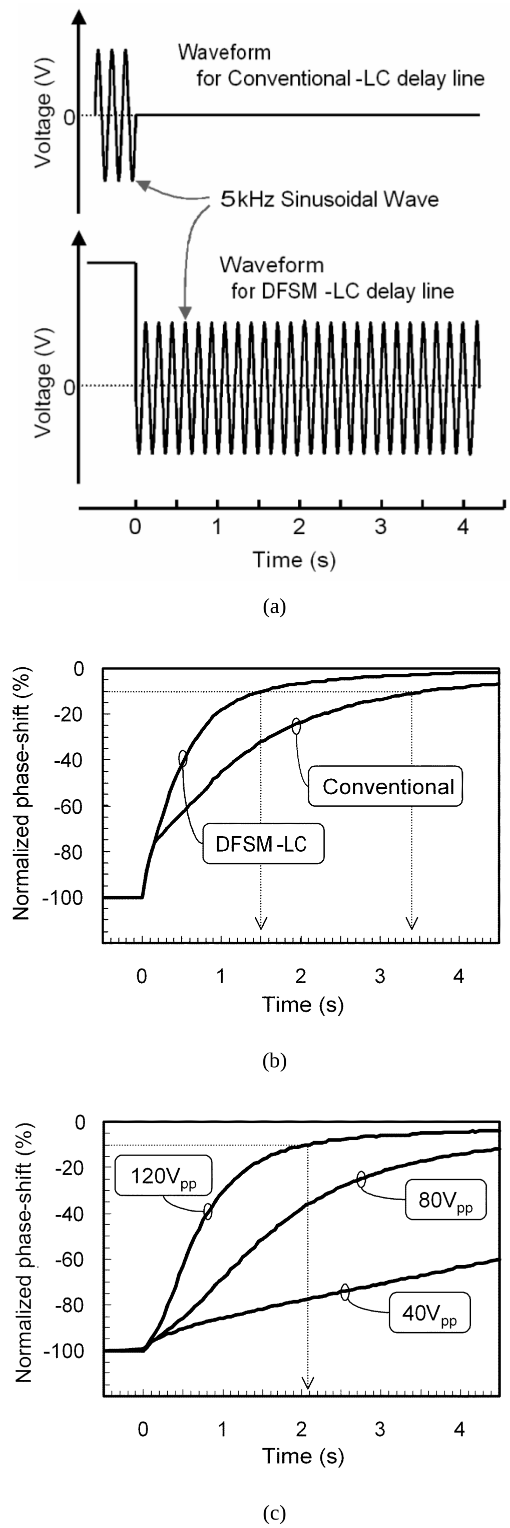

Fig. 8. Transient responses in the phase shift of the variable delay lines. (a) Control voltage waveform for measuring the transient responses in the phase shift. (b) Comparison of conventional with the DFSM LC for the response of the delay lines with 50-μm-thick LC layers for the change in control voltage from 60-V dc to the 5-kHz sinusoidal wave of 40 V_{pp}. (c) Dependencies on the high-frequency control voltages for the variable delay line with 200-μm-thick LC layer.

Fig. 8(b) shows the transient responses in the phase shift of the variable delay lines that used the DFSM LC and the conventional ones for the 50-μm-thick LC layer. The horizontal axis in this figure shows the time elapsed since the control voltage was changed and the vertical axis shows the phase shift normalized to the initial phase shift before being triggered. For the conventional LC, the phase-shift decay time for a change in the control voltage of a 5-kHz sinusoidal wave from 40 to 0 V_{pp} was 3.4 s, but the decay time of the DFSM LC was 1.5 s for a change in the control voltage from 60-V dc to a 5-kHz sinusoidal wave of 40 V_{pp}, which was less than half the time for the conventional LC. This result shows that using the DFSM LC enabled the decrease of the phase-shift response time for a given LC layer thickness.

Fig. 8(c) shows the transient responses in the phase shift of the DFSM-LC variable delay line with an LC layer thickness of 200 μm, and it shows the change in phase shift in the case where the control voltage was changed from 100-V dc to a 5-kHz sinusoidal wave, with its voltage as the parameter. Making the voltage of the 5-kHz sinusoidal wave large shortened the decay time, resulting in a decay time of 2.1 s for 120 V_{pp} of a 5-kHz sinusoidal wave. The transient responses in the phase shift for the 50-μm conventional LC variable delay line is also shown in Fig. 8(b). This result demonstrates that the phase-shift decay time for even the thick LC layer is almost the same as that of the conventional LC variable delay line with a thin LC layer. From Figs. 7 and 8(c), it is apparent that the insertion loss was reduced without increasing the phase-shift decay time, even if the LC layer was thick.

IV. CONCLUSION

In this paper, we have described a method of reducing the insertion loss and response time in the phase shift in a microwave variable delay line using DFSM LC. By using the characteristic of DFSM LC, the alignment of which can be controlled with the frequency of the control voltage, the LC alignment can always be driven by applying a combination of dc and several kilohertz control voltages. Through the experiments, we have confirmed the following.

- The phase-shift decay time can be reduced without making the LC layer thinner. The decay time of the variable delay line with a 50-μm-thick DFSM-LC layer was 1.5 s, which is less than half the time required for the conventional device.
- The insertion loss can be reduced without increasing the phase-shift decay time, even if the LC layer is thick. A 9-dB reduction of the insertion loss was achieved by using a 200-μm-thick DFSM-LC layer.

One of the applications of the delay line described here may be a phased-array antenna, which can steer the beam electronically. The reduction of the insertion loss can prevent the antenna system from becoming complex, and the fast response of the phase shift makes the beam steering rapidly. However, it would be desired to make further reduction of the insertion loss and response time in the phase shift in order to apply it to various microwave signal processings.

In a future paper, we will investigate the application of the variable delay line proposed here to the millimeter-wave range in addition to its microwave range application.

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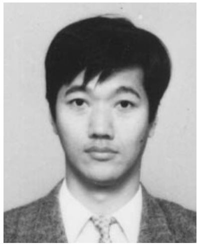

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