Microwave Variable Delay Line using a Membrane Impregnated with Liquid Crystal

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***Abstract* — A microwave variable delay line using a membrane impregnated with liquid crystal was newly fabricated. By employing the membrane impregnated with liquid crystal to the liquid crystal layer of the delay line, the phase-shift response becomes fast independently of the liquid crystal thickness. Experimental results show that the phase-shift response time of 33 ms, which is two orders of magnitude faster than that of a conventional one, is obtained. The new delay line also exhibits a 270-degrees phase-shift and non-dispersive delay characteristics over a wide microwave-frequency range. Moreover, it is clarified that the phase-shift characteristics to a control voltage depend on a pore size of the membrane.**

I. Introduction

Tunable microwave devices, which can electronically vary the amplitude, phase, or frequency of a microwave signal, have been widely applied in modern radio systems, and have become the target of recent investigations. There has been research on variable delay lines [1], variable oscillators [2], and other devices that use the magnetostatic mode, and lately, a variable resonator [3] and a variable phase shifter [4][5] using ferroelectric materials have been reported. It has been explained that the amplitude, phase, and other transmission characteristics of a microwave signal can be controlled by an external signal, which changes the permittivity of the dielectric material and/or the permeability of the magnetic material.

Attention has been drawn to liquid crystal (LC) because its permittivity can be changed, which makes it attractive for use as a dielectric substrate material for microstrip lines. The alignment of molecules of LC can be changed by changing an external bias electrical field, and it is known that the permittivity of LC changes in accord with the LC alignment [6]. Using this phenomenon, some researchers have endeavored to invent a microwave and millimeter-wave transmission line whose transmission characteristics can be controlled externally. K.C. Lim et al. reported a millimeter-wave variable phase shifter formed by a waveguide filled with nematic LC, and the LC is controlled by a bias voltage [7]. D. Dolfi et al. also reported a variable phase shifter in the microwave and millimeter-wave band that uses nematic LC for the dielectric substrate of a microstrip line [8][9].

The authors have lately been researching devices to control microwaves using LC [10][11], and have successfully demonstrated a LC variable delay line in a wide microwave range. Simultaneously, they have also clarified some problems of LC variable delay lines. One of these problems is a slow phase-shift response time in accord with a change in the control voltage. The phase-shift response time was found to be especially slow (several seconds) when the control voltage is removed.

This paper demonstrates that the phase-shift response time can be reduced by using a membrane impregnated with LC (MI-LC) for the dielectric substrate of the microstrip line, and presents experimental results for a microwave variable delay line using MI-LC.

II. Principle

Fig. 1 shows the structure of an LC microwave variable delay line, the LC layer of which is the space between the ground metal and the cover substrate. Here, the MI-LC is applied to the LC layer. By applying a control voltage between the strip conductor and the 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.

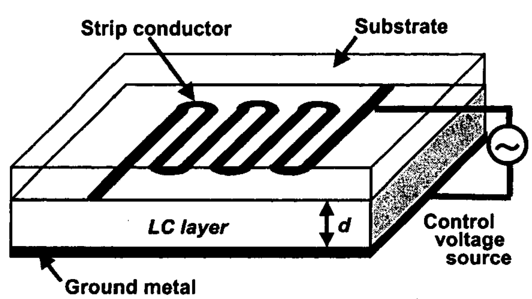

Fig. 1. Structure of the variable delay line using LC.

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In a conventional variable delay line, the LC layer is composed of only LC material. The phase-shift response to change of the control voltage (i.e., a response of changing an LC alignment) is slow because the LC layer thickness (d, shown in Fig. 1) is very large compared with that used in ordinary LC display devices. Generally, the response time of the LC alignment increases in proportion to the square of LC layer thickness. Considering that the response time of ordinary display devices with LC layer thickness of 10 μm or less is some tens of milliseconds [12], one can be convinced that the response time of a conventional variable delay line with LC layer thickness of 50 μm would become several seconds. On the other hand, a thick LC layer is desired from the viewpoint of lowering the insertion loss of the delay line, and this conflicts with making the phase-shift response fast.

Employing a PTFE membrane impregnated with nematic LC can solve this problem. The membrane can exist near the LC molecules even if the LC layer becomes thick, as shown in Fig. 2. This has the same effect in LC alignment as making the LC layer thin. Consequently, the phase-shift response of the variable delay line becomes fast independently of LC layer thickness. Moreover, the alignment layer, which is normally attached on the substrate, becomes unnecessary.

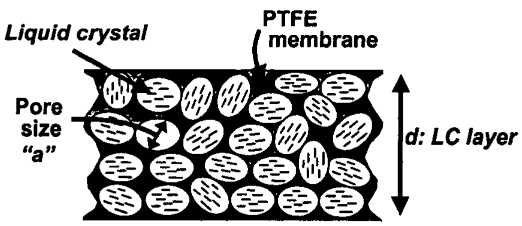

Fig. 2. Structure of the MI-LC.

III. EXPERIMENTS

A. Design and fabrication

An experimental microstrip-line-type variable delay line using MI-LC was designed and fabricated as shown in Fig. 1. The design parameters are listed in Table 1. And commercial membranes were used in this experiment. The porosity rate of these membranes, i.e., the LC content of the MI-LC layer, was chosen to be 80 %, and these membranes thickness, i.e., LC layer thickness, was chosen to be 100 μm. In order to set the characteristic impedance of the microstrip line at 50 Ω, the line width was set to be 200 μm. The line length was 193 mm. The same nematic LC for the conventional variable delay line was also employed here. The mean pore sizes in the membranes of 1, 5 and 10 μm were chosen to investigate the influence of the pore size to the phase-shift characteristics of the variable delay line.

TABLE I
DESIGN PARAMETERS OF THE VARIABLE DELAY LINE USING MI-LC.

LC layer	Thickness (d)	100 μm
	$\varepsilon_{r(LC)}$	3
	tanδ	0.01
Substrate	Thickness	525 μm
	$\varepsilon_{r(substrate)}$	3.77
	tanδ	negligible
Strip conductor	Thickness	1 μm
	Width	200 μm
	Resistivity	2.44×10^{-8} Ωm

B. Results and discussions

The fabricated variable delay line was examined by measuring the phase-shift characteristics for changes of the control voltage, and the phase-shift response time for the control voltage. The measurement set-up for evaluating the characteristics is shown in Fig. 3. The control voltage is superimposed on the microwave by the bias-T and applied to the variable delay line. The phase-shift are measured by the vector network analyzer.

Fig. 4 shows the phase-shift characteristics of the experimental variable delay lines using MI-LCs with different pore-sizes. The measurement frequency was 20 GHz. A 5-kHz sinusoidal wave was used for the control

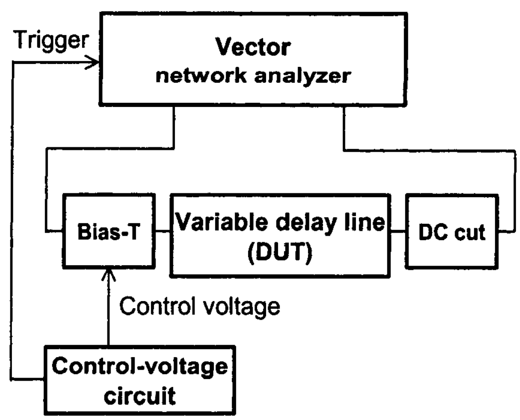

Fig. 3. Measurement set-up for characteristic evaluation.

voltage in the phase-shift measurement. By varying the control voltage from 0 V_{pp} to 450 V_{pp}, a 270-degree phase-shift was achieved, for pore size of 10 μm. This is about 3/4 the maximum phase-shift of 370 degrees in the conventional variable delay line measured in the same manner. Possible causes of the smaller phase-shift are that the permittivity of the membrane constituting the MI-LC dose not change by changing the control voltage and the alignment of the LC is not uniform when control voltage was 0 V_{pp}.

From the figure, it is also clear that a large control voltage was required for a phase-shift as the pore size decreased. This is because the anchoring effect (*1) of the membrane surface on the LC molecules becomes larger and the voltage required to align the LC also becomes larger as pore size decreases.

The frequency-to-phase-shift characteristic for a control voltage of 450 V_{pp} is shown in Fig. 5. The phase-shift is proportional to the input microwave frequency, that is, it increases linearly with increasing frequency. These results show that the variable delay line is non-dispersive over a wide microwave-frequency range.

The transient response in the phase-shift was measured when the control voltage of 5-kHz sinusoidal wave was changed in steps from 450 V_{pp} to 0 V_{pp}. The results for the delay line with pore size of 10 μm are shown in Fig. 6. The horizontal axis is the lapsed time since the control voltage is changed. The vertical axis is the phase-shift normalized to the initial phase-shift before it is triggered. The measurement frequency was 5 GHz. The response time (*2) of 33 ms was obtained, which is two orders of magnitude faster than the conventional one's. As a result, it was shown that the phase-shift response was drastically improved by using the MI-LC.

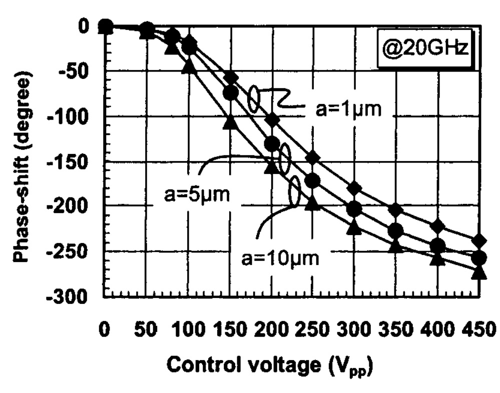

Fig. 4. Phase-shift characteristics of the variable delay line using MI-LC, measured at 20 GHz.

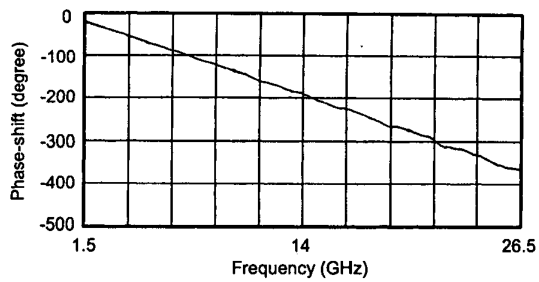

Fig. 5. Phase-shift for different frequencies of the delay line with pore size of 10 μm, measured at control voltage of 450 V_{pp}.

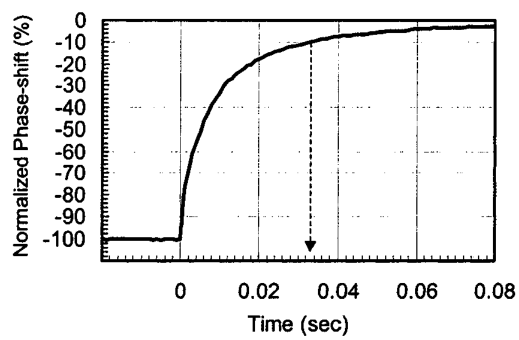

Fig. 6. Phase-shift response of the variable delay line with pore size of 10 μm at measured frequency of 5 GHz.

IV. Conclusion

The microwave variable delay line using the MI-LC was newly fabricated. By employing the MI-LC to the LC layer of the delay line, the phase-shift response becomes fast independently of the LC thickness. A phase-shift response time of 33 ms, which is two orders of magnitude faster than the conventional one's, was obtained. The new delay line also exhibited the 270-degrees phase-shift and non-dispersive delay characteristics over a wide microwave frequency range. In addition, it was found that the phase-shift characteristics for the control voltage depend on the pore size of the membrane.

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(*1) Anchoring is the force that orients the LC molecules to their initial alignment.

(*2) Response time is defined as the time it takes for a decrease in phase-shift to reach 10 % of saturation.