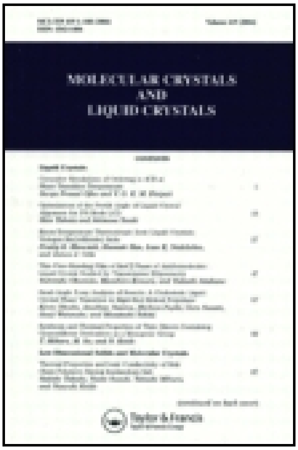

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Microwave High-Speed Liquid Crystal Devices Using CPW with Floating Electrode

Yozo Utsumi [a], Toshihisa Kamei [a], Takehiko Maeda [a] & Nguyen Quoc Dinh [a]

[a] Department of Communications Engineering, National Defense Academy, Yokosuka-shi, Kanagawa, Japan

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Yozo Utsumi
Toshihisa Kamei
Takehiko Maeda
Nguyen Quoc Dinh
Department of Communications Engineering, National Defense Academy, Yokosuka-shi, Kanagawa, Japan

We develop a transmission line with a floating electrode (FE) arranged on a coplanar waveguide (CPW), and we propose using this transmission line to reduce the decay time of a microwave-band liquid crystal loaded device. Using the proposed CPW-FE structure makes it possible to control both the rise time and decay time by varying the applied bias field, thereby allowing the decay time to be reduced. In the 18 GHz band variable phase shifter we developed, we obtained a rise time of 75 ms and a decay time of 200 ms with a 500 μm wide CPW center conductor, a gap of 20 μm between the center conductor and ground plane, and a liquid crystal layer thickness of 50 μm. Under these conditions, the birefringence $\Delta\varepsilon'$ of the liquid crystal was 0.23.

Keywords: coplanar waveguide; delay line; liquid crystal devices; phase shifter

INTRODUCTION

Almost all microwave-band liquid crystal devices (e.g., variable delay lines and variable phase shifters) have been developed using microstrip-line (MSL) structures [1–6].

In a liquid crystal device with a microstrip-line structure, microwave-band insertion losses make it impossible to use an extremely thin liquid crystal layer as in liquid crystal display applications. On the other hand, the decay time of a liquid crystal device increases in

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Address correspondence to Yozo Utsumi, Department of Communications Engineering, National Defense Academy Hashirimizu 1-10-20, Yokosuka-shi, Kanagawa, 239-8685, Japan. E-mail: yutsumi@mda.ac.jp

proportion to the square of the layer thickness [7]. Therefore, with a liquid crystal layer thickness of approximately 100 μm, the decay time ends up being approximately 1000 times greater than the rise time [5].

It is thus hoped that a way can be found to substantially reduce the decay time and deterioration of the dielectric properties.

With regard to controlling the response time, the methods mentioned in references [1–6] control the rise time with the strength of the bias field, while the decay time is controlled by mechanical constraining forces produced by rubbing the polyimide films formed at both boundary surfaces of the liquid crystal layer, and the speed of this decay is thus limited for any liquid crystal layer of finite thickness. Compared with the devices using plain liquid crystals as in references [1–5] (where the decay time is 20 s for a 100 μm thick liquid crystal layer), the decay time of the device in reference [6], which uses a polymer dispersed liquid crystal, could be reduced to 650 ms for a 50 μm thick polymer dispersed liquid crystal layer by optimizing the material composition. In this article, with the aim of controlling the decay time by a bias field in the same way as the rise time, thereby reducing the decay time, we propose a high-speed variable phase shifter where a coplanar waveguide (CPW) with a floating electrode (CPW-FE) is filled with a plain liquid crystal without rubbing in an effort to control the orientation of the liquid crystal molecules by changing the direction of the bias field.

RESPONSE TIME AND TRANSMISSION LOSS OF MICROSTRIP-LINE LIQUID CRYSTAL DEVICES

We will investigate the relationship between response time and transmission loss in liquid crystal devices with an MSL structure.

When a plain liquid crystal is injected between two parallel plates that have been subjected to a rubbing process, the rise time (τ_r) and decay time (τ_d) are expressed as follows [1]:

$$\tau_r = \eta / \left\{ \varepsilon_0 |\Delta\varepsilon'| (E_0^2 - E_C^2) \right\} \tag{1}$$

$$\tau_d = \eta d^2 (\pi^2 k) \tag{2}$$

Here, η is the coefficient of viscosity, E_0 and E_C are the bias electric field and threshold electric field, $\Delta\varepsilon'$ ($= \varepsilon'_{\|} - \varepsilon'_{\perp}$) is the dielectric birefringence, and k is the elastic constant. As Eq. (2) shows, the decay time increases in proportion to the square of the liquid crystal layer thickness d, so once d has been set, the device's τ_d is more or less predetermined. The thickness of the liquid crystal layer for microwave devices is relatively large at about 100 μm, in which case the rubbed substrate surfaces are only able to apply a weak aligning force to the molecular orientation of the liquid crystal so that the rise time is only a few milliseconds while the decay time is much longer at several tens of seconds.

As Eq. (1) shows, a larger bias field results in a smaller τ_r, but since τ_d is proportional to the square of d, d has to be reduced to obtain a smaller τ_d. According to the measurement results of reference [5], when $d = 100\,\mu m$, τ_d is approximately 20 s for a bias voltage of $V_0 = 150\,V$. Based on this value, and using equation (2), d must be brought right down to 20 μm to reduce τ_d to 800 ms. On the other hand, if d is reduced then the width W of the center conductor must also be reduced in order to keep the characteristic impedance Z_0 of the line at 50 Ω. Assuming the liquid crystal layer has a permittivity of about 3, this means that W must be reduced to 43.5 μm when $d = 20\,\mu m$, resulting in a large transmission loss due to conductor losses.

TRANSMISSION LOSS OF MICROSTRIP-LINE AND COPLANAR WAVEGUIDE

We discuss the transmission loss of an MSL structure and a CPW structure. In MSL structure, W is the width of the MSL center conductor, and d is the thickness of the liquid crystal layer, both sides of which have been subjected to a polyimide film rubbing process. In CPW structure, W is the width of the CPW center conductor, S is the separation between the end of the center conductor and the ground plane, and h is the thickness of the dielectric substrate. Figure 1 shows the relationship between characteristics impedance Z_0 and center conductor width W in devices with MSL and CPW structures where $\varepsilon_r = 3$, $d = 20\,\mu m$, $s = 20\,\mu m$, $h = 40\,\mu m$.

For the MSL's and CPW's figures in Figure 1, it is assumed that the dielectric substrate has a relative permittivity of 3. In both figures, the thickness t of the conductors constituting parts such as the center conductor is assumed to be zero.

Also, if we assume fixed dimensions of $d = 20\,\mu m$ and $S = 20\,\mu m$, $h = 40\,\mu m$, then the characteristic impedance Z_0 is determined by W in MSL and by $W/(W + 2S)$ in CPW [8]. In reference [8], the relationship between Z_0 and W in CPW is determined for the case where the dielectric substrate is made of alumina (relative permittivity 10). We repeated the calculations of reference [8] to a first approximation for a relative permittivity of 3, and the results are shown in Figure 1.

As this figure shows, a characteristic impedance of $Z_0 = 50\,\Omega$ is obtained when $W = 43.5\,\mu m$ in an MSL device, and when $W = 760\,\mu m$ in a CPW device.

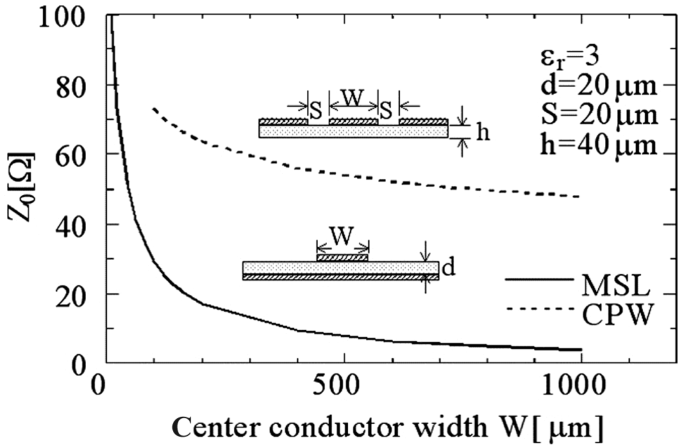

FIGURE 1 The relationship between characteristic impedance Z_0 and center conductor width W in devices with MSL and CPW structures (calculated values).

Next, we used the method of reference [8] to approximate the relationship between the transmission loss (L dB/cm) and W based on the conductor losses at 20 GHz under the above conditions. The results are shown in Figure 2. In both lines, the electromagnetic field

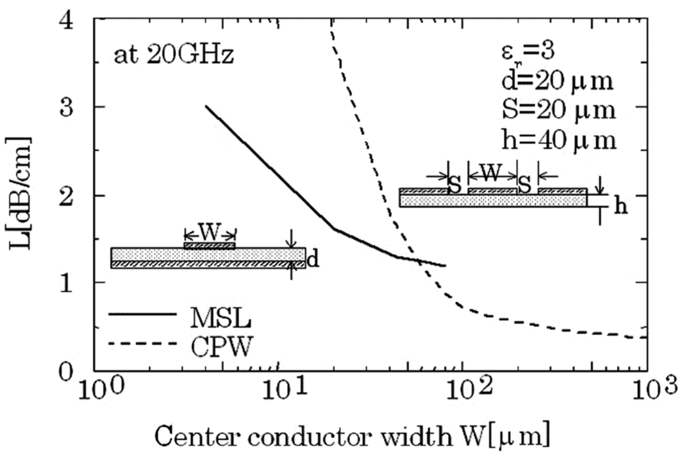

FIGURE 2 The relationship between transmission loss and center conductor width W based on conductor losses in MSL and CPW devices (calculated values).

distribution indicates that the transmission loss originating from conductor losses is greatly affected by the width of the center conductor. In an MSL device, since d is fixed at 20 μm, this loss is determined solely by the small value of W, so the transmission loss becomes big. On the other hand, in a CPW device, W does not necessarily have to be made small. When $Z_0 = 50\,\Omega$, we obtain $W = 43.5\,\mu m$ and $L = 1.29$ dB/cm for an MSL device, while for a CPW device we obtain $W = 760\,\mu m$ and a smaller transmission loss of $L = 0.4$ dB/cm.

Accordingly, in an MSL structure, if replacing the dielectric substrate with a liquid crystal layer whose permittivity is also about 3, to get a decay time τ_d of substantially less than 1 s by relying solely on the mechanical constraining force resulting from rubbing, d has to be made extremely small, making this type of structure impractical from the viewpoint of transmission losses in the design of a high-speed liquid crystal device.

On the other hand, for a liquid crystal device with a CPW structure where a liquid crystal layer of about 50 μm is supposed to be situated on a CPW substrate, if a bias voltage can be applied between the center conductor and ground plane, then this means it is possible to increase the bias field by making S smaller, which contributes to reducing the rise time τ_r. (The rise time is defined as the time when the liquid crystal molecules become aligned in the direction in which an electric field is applied from the center conductor to the ground planes on both sides.)

However, in this structure, the liquid crystal molecules cannot be oriented perpendicular to the plane of the center conductor and ground plane in a cpw device. In the following sections, we discuss a structure in which the liquid crystal molecules can be aligned perpendicularly by a bias field.

A LIQUID CRYSTAL COPLANAR WAVEGUIDE DEVICE WITH A FLOATING ELECTRODE (CPW-FE)

To enable the alignment of the liquid crystal molecules to be controlled by an applied bias field even in a direction perpendicular to the CPW substrate, we developed a coplanar waveguide with a floating electrode oriented parallel to the substrate plane (CPW-FE) as shown in Figure 3. Figure 3(a) shows the case where the bias field is applied between the CPW center conductor and ground plane, and Figure 3(b) shows the case where it is applied between the FE and CPW center conductor and the ground plane. In Figure 3(a), the longitudinal axes of the liquid crystal molecules are aligned in the direction of the bias field, which more or less matches the direction of the high-frequency

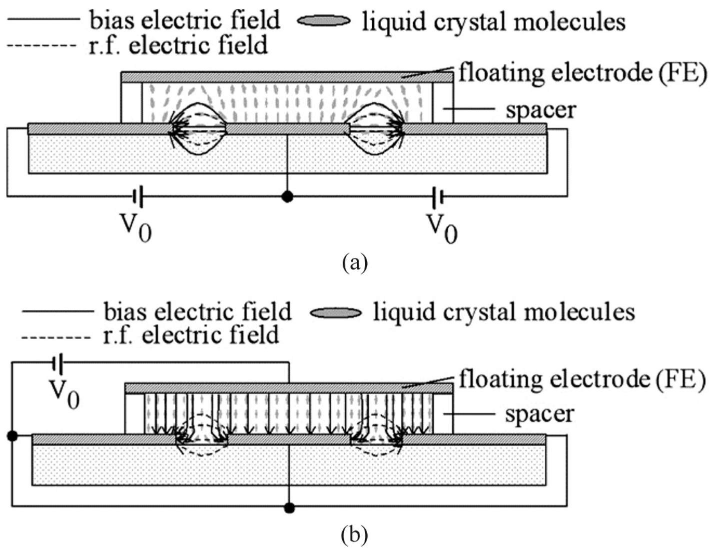

FIGURE 3 Liquid crystal molecules' alignment in a CPW-FE device. (a) Liquid crystal molecules' alignment when a positive voltage is applied to the center conductor. (b) Liquid crystal molecules' alignment when a positive voltage is applied to the floating electrode.

electric field in the dominant mode of the CPW device, near the gap between the center conductor and the ground plane of the CPW. We will use the notation $\varepsilon'_{||}$ to represent the relative permittivity of the liquid crystal when the longitudinal axes of the liquid crystal molecules match the direction of the high-frequency electric field in this way. Meanwhile, in Figure 3(b), the direction of the bias field is perpendicular to the direction of the high-frequency electric field of the CPW device near the gap.

We will use the notation $\varepsilon'_{\perp}$ to represent the relative permittivity when the longitudinal axes of the liquid crystal molecules are perpendicular to the direction of the high-frequency electric field.

The distribution of the high-frequency electric fields in the CPW-FE is shown in Figure 4 as the computer simulation results. The size and darkness of arrows indicate the strength of the electric field. For the electromagnetic field simulations, we employed 3D electromagnetic simulation software called MW Studio (from CST) and used the finite integration technique (an algorithm for solving Maxwell equations in integral form) and the perfect boundary approximation technique (an expanded algorithm using a cubic mesh that can perform analysis

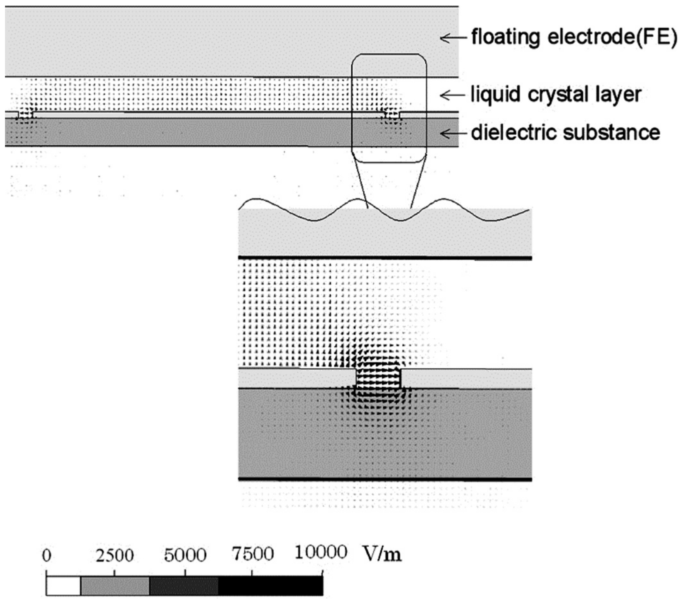

FIGURE 4 The high-frequency electric field in the liquid crystal layer (simulated values).

while preserving complex shape information including surfaces) as analysis techniques.

The high-frequency electric field near the gap is almost parallel to the CPW substrate, and its strength is very large compared with the one far from the gap.

By switching between the bias voltage application methods shown in Figure 3(a) and (b) as described above, it is possible to use bias fields in two directions to control the liquid crystal molecules so that they are aligned parallel with or perpendicular to the high-frequency electric field of the CPW device. We will refer to the response time of the liquid crystal molecules when the bias field is switched from (b) to (a) as the rise time (τ_r), and to the response time of switching from (a) to (b) as the decay time (τ_d).

RESULTS AND DISCUSSION

We discuss a liquid crystal loaded variable phase shifter using a CPW-FE structure. We consider the case of liquid crystal loaded variable phase shifter with the following properties: substrate thickness: h = 40 μm, substrate relative permittivity: 2.6, S = 20 μm, W = 500 μm,

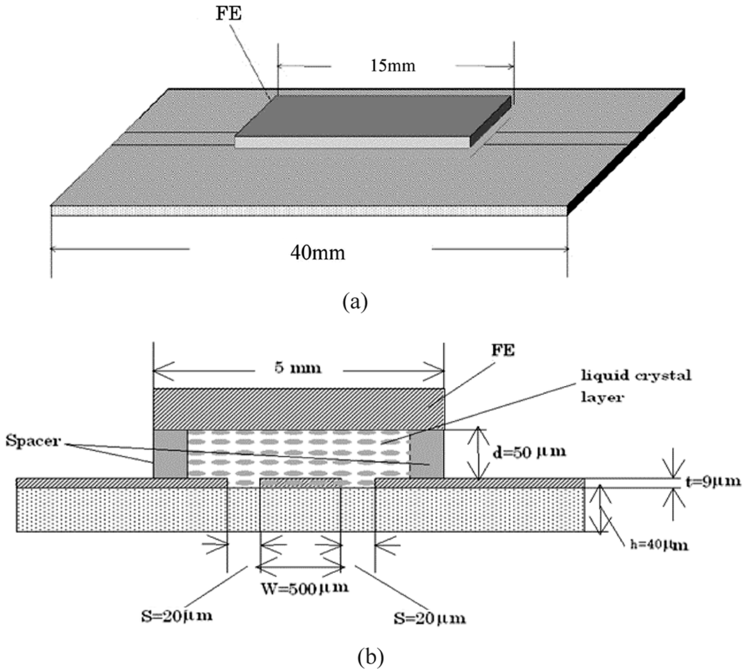

FIGURE 5 External view and cross section of a CPW-FE device. (a) External view. (b) Cross section.

line length $l = 40\,\text{mm}$, conductor thickness: $t = 9\,\mu\text{m}$, nematic liquid crystal (BL006) layer thickness: $d = 50\,\mu\text{m}$, and nematic liquid crystal BL006 is injected between the FE and CPW of the structure shown in Figure 5 only in the 15 mm long region directly underneath the FE.

When a bias voltage is applied as shown in Figure 3(a), the alignment direction of the liquid crystal molecules more or less coincides with the direction of the high-frequency electric field in the CPW device, so it exhibits a permittivity of $\varepsilon'_{||}$, while in Figure 3(b) it exhibits a permittivity of $\varepsilon'_{\perp}$. It is possible to design a variable phase shifter by switching between these two bias voltage states and using the resulting difference in phase values corresponding to $\varepsilon'_{||}$ and $\varepsilon'_{\perp}$.

We therefore need to determine the variable phase shift corresponding to a CPW-FE device per 15 mm length of liquid crystal. Figure 6 shows how this phase shift varies with the bias voltage (experimental values), based on measurements made at a frequency of 18.4 GHz. Figure 6 also shows the results of determining the birefringence $\Delta\varepsilon'$

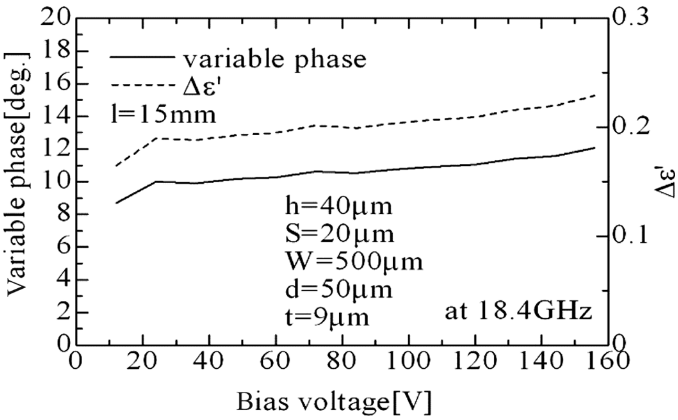

FIGURE 6 The relationship between variable phase shift, birefringence and bias voltage (experimental values).

($=\varepsilon'_{||}-\varepsilon'_{\perp}$) of the nematic liquid crystal BL006 injected into the CPW-FE structure based on the above mentioned results.

At a bias voltage of 150 V or more, we obtained a variable phase shift of 12° and a $\Delta\varepsilon'$ of 0.23 — this value is only about half as good as the value of $\Delta\varepsilon' = 0.45$ measured at 20 GHz when BL006 liquid crystal was filled into a MSL structure [5].

To increase the value of $\Delta\varepsilon'$ in a CPW-FE structure, it would probably be worthwhile conducting further studies aimed at optimizing the liquid crystal layer thickness d, the FE electrode structure, and the parameters S and W of the CPW structure.

Finally, Figure 7 shows the relationship between the rise time (τ_r), decay time (τ_d), and bias voltage of a liquid crystal loaded variable phase shifter with a CPW-FE structure (experimental values).

At a bias voltage of 150 V or above, we obtained $\tau_r = 75$ ms and $\tau_d = 200$ ms. By way of comparison, when a BL006 liquid crystal layer (50 μm thick) was used as the dielectric layer in a MSL structure, the resulting values were $\tau_r = 5$ ms, $\tau_d = 5$ s, and $\Delta\varepsilon' = 0.45$ [5], and when using a polymer dispersed liquid crystal layer made with nematic liquid crystal BL011 (50 μm thick), the resulting values were $\tau_r = 30$ ms, $\tau_d = 650$ ms, and $\Delta\varepsilon' = 0.28$ [6].

Although a CPW-FE structure results in worse values for τ_r and $\Delta\varepsilon'$, it substantially improves τ_d. In particular, τ_d is reduced to just one twenty-fifth of the value obtained with a plain liquid crystal in reference [5].

Since the method of references [5–6] involves controlling τ_d with a mechanical constraining force due to the rubbing process applied to both sides of the liquid crystal layer, τ_d is more or less fixed for a given

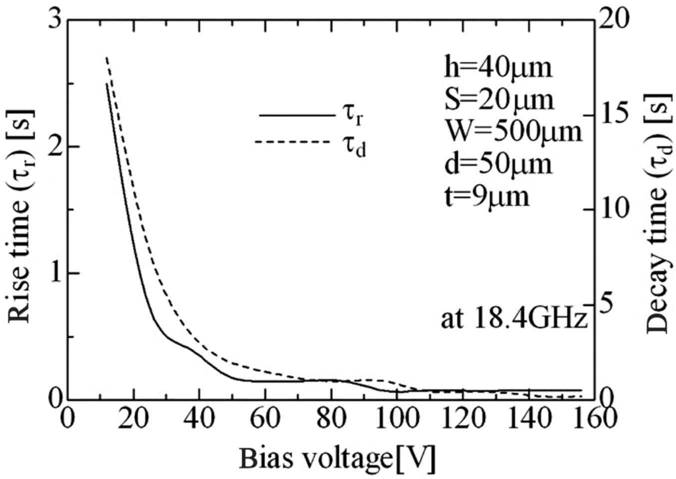

FIGURE 7 The relationship between τ_r, τ_d and bias voltage in a liquid crystal loaded variable phase shifter with a CPW-FE structure (experimental values).

value of the liquid crystal layer thickness d, leaving little scope for improvement.

Meanwhile, in our proposed method τ_d is also controlled by an applied bias field, so it is expected that further improvements can be made in the future by optimizing the circuit structure.

CONCLUSION

In the development of a microwave-band liquid crystal loaded device, we have found a method whereby the response time taken to align the nematic liquid crystal molecules with the direction of a high-frequency electric field (rise time) and the time taken to align them perpendicular to this direction (decay time) can both be controlled simply by adjusting an applied bias field. Specifically, we have proposed a structure consisting of a coplanar waveguide with floating electrode (CPW-FE), and we have shown that it can achieve decay times far superior to those achievable with the conventional method of applying a mechanical constraining force by rubbing. In the 18.4 GHz band, we obtained a rise time of $\tau_r = 75$ ms and a decay time of $\tau_d = 200$ ms. We also obtained a variable phase shift of 12° in a line length of 15 mm, which corresponds to a birefringence of $\Delta\varepsilon' = 0.23$. Based on these experimental results, we plan to develop a phase shifter with an about 220 mm long meander line structure that should be able to vary the phase by up to 180°.

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