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Conductor loss reduction for liquid crystal millimeter-wave beam former

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Abstract: Means of reducing the conductor loss of a liquid crystal millimeter-wave beam former were studied. The conductor loss is caused by surface currents flowing on electrodes of the beam former for applying control voltages to the liquid crystal layers. By making the electrode thickness comparable to or thinner than the skin depth, the surface currents that flow on both sides of the electrode in opposite directions cancel each other; consequently, the conductor loss can be reduced. Simulation results proved that doing so can effectively reduce the conductor loss.

Keywords: conductor loss, skin depth, conductivity, millimeter wave, liquid crystal, beam steering

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

A millimeter-wave beam former using liquid crystal (LC), which can electrically steer and/or shape a millimeter-wave beam, has been previously reported [1, 2]. It utilizes the feature by which LC changes its permittivity according to a control voltage. The beam former is constructed by simply stacking LC layers and electrodes connected to control voltage sources, as shown in Fig. 1. The control voltage is used to vary the permittivity of each LC layer, thereby shifting the phase of the millimeter wave passing through the layer. Consequently, the phase distribution can be varied across the stacked LC layers to steer and/or shape the millimeter wave beam.

The insertion loss of the beam former, which is composed of the dielectric loss of the LC and the conductor loss due to surface currents flowing on the electrodes, was investigated and shown to be too large for practical use [1, 2]. The well-known methods to reduce this loss, especially the conductor loss, are the use of high-temperature superconductor as the electrode material [3] and optimization of the current distribution of the transmission lines [4, 5]. In this letter, we study a simple method for the LC beam former that exploits the feature of surface currents flowing on both sides of the electrode but in opposite directions. In particular, we show that the surface currents are cancelled by thinning the electrodes and that this can reduce the conductor loss of the beam former. The principle of the conductor loss reduction is presented, and simulation results are shown to verify our method.

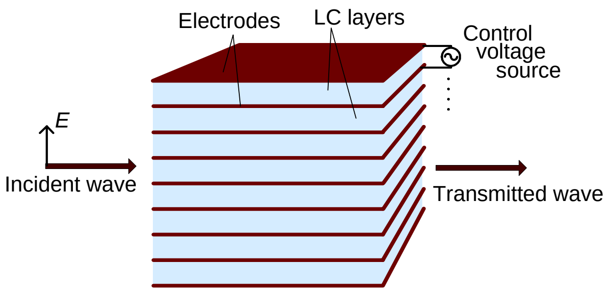

Fig. 1. Structure of the beam former [1, 2].

2 Principle

The millimeter-wave propagation in each LC layer can be regarded as the TEM mode, if the incident wave is polarized perpendicular to the electrodes and the distance between the electrodes is shorter than a half wavelength of the millimeter wave. In such a case, the surface currents flow on the electrodes as shown in Fig. 2, and this leads to the conductor loss. The surface-current densities, indicated as J_+ and J_- in Fig. 2, are distributed in the depth

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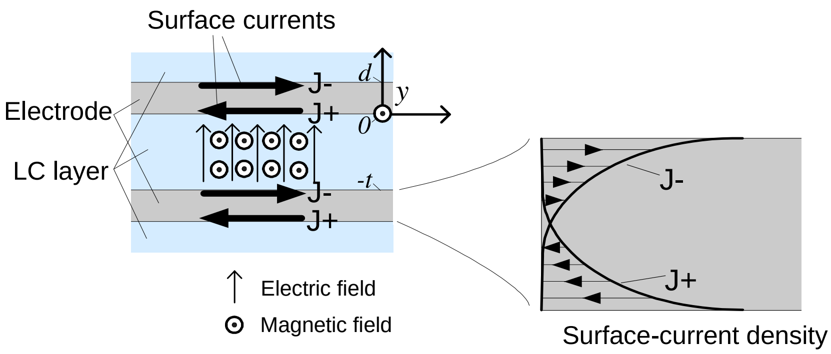

Fig. 2. Surface currents flowing on the electrodes.

direction of the electrode, and flow in opposite directions on either side of the electrode. Hence they could cancel each other if the electrode thickness could be made less than the order of the skin depth, and consequently, the total surface current, or conductor loss, could be reduced. The surface-current densities J_+ and J_- can be expressed as,

$$J_+(x) = J_0 e^{-\frac{1+i}{\delta}x} \quad (1)$$
$$J_-(x) = -J_0 e^{\frac{1+i}{\delta}(x-d)}, \quad (2)$$

considering not only the attenuation constant but also the phase constant in the electrode [7], where d and δ are the electrode thickness and the skin depth, respectively. x is the distance from the electrode surface, and J_0 is the magnitude of the surface-current density at the surface.

The conductor loss per unit length along the propagation direction P_l caused by these surface currents can be derived by integrating the product of the resistivity and the square of the current density with respect to the cross section of the electrode. The surface-current density should be the superimposition of J_+ and J_-, and both the upper and lower conductors of the waveguide should be taken into account. Assuming the width of the electrode, or the length along the y-axis, to be of unit length, we have,

$$P_l = 2 \times \int_0^{\frac{d}{2}} \frac{1}{\sigma} |J_+(x) + J_-(x)|^2 dx, \quad (3)$$

where σ represents the conductivity of the electrodes. Then substituting Eq. (1) and (2) into (3), we obtain,

$$P_l = \frac{\delta}{\sigma} J_0^2 (1 - e^{-\frac{2d}{\delta}} - 2e^{-\frac{d}{\delta}} \sin(d/\delta)). \quad (4)$$

The attenuation constant α_c is derived from the relation between P_l and the power flow along the waveguide (See appendix A for the full derivation),

$$\alpha_c = \frac{1}{\sigma\delta\eta t}(1 - e^{-\frac{2d}{\delta}} - 2e^{-\frac{d}{\delta}} \sin(d/\delta)). \quad (5)$$

where η and t denote the wave impedance and the thickness of the LC layer, respectively. Note that in practice t can not be increased to reduce α_c because a higher control voltage is needed if t becomes larger.

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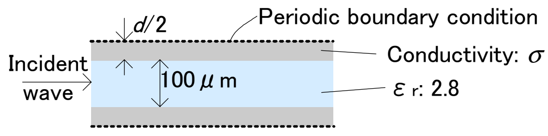
In case of the conventional beam former, the electrode thickness d has a large value compared with δ, so that α_c is nearly equal to the attenuation constant of a parallel-plate waveguide, $\alpha_{ppw} = 1/\sigma\delta\eta t$. It appears that if $d/\delta < 2$, α_c can take a smaller value than α_{ppw}. Therefore, the conductor loss of the beam former can be reduced if the d/δ is small enough.

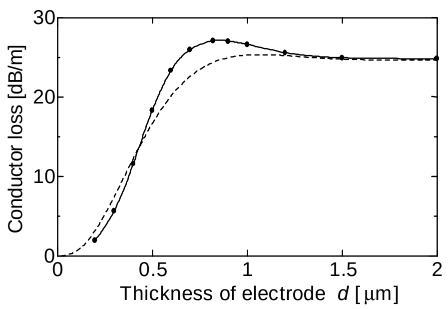
Note that the electromagnetic field in an LC layer could be leaked to the adjacent LC layers when d/δ is small. While this may degrade the phase distribution characteristics of the beam former, if the leakage is sufficiently small, its influence on the behavior of the beam former can be neglected in practice, as is estimated in appendix B

3 EM Simulation results and discussion

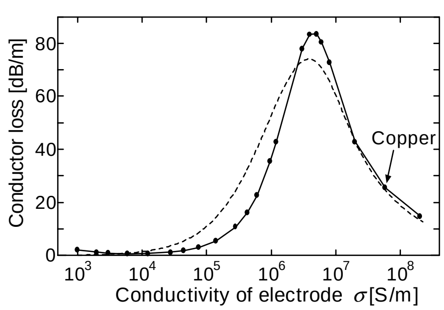
To verify the above-mentioned principle, the conductor losses as a function of d/δ were simulated using the model shown in Fig. 3 (a). (The EM simulator was CST MICROWAVE STUDIO®.)



(a)



(b)



(c)

Fig. 3. (a) Simulation model. (b) Conductor loss as a function of electrode thickness. (c) Conductor loss as a function of the conductivity of the electrodes. Solid lines with solid circles represent the simulation results and dashed lines represent the analytical results of Eq. (5).

Firstly, the electrode thickness d is reduced to make d/δ small. Figure 3 (b) shows the simulation results of the conductor loss versus d when the conductivity of the electrode is 5.8×10^7 S/m (copper) and the frequency is 60 GHz. The analytical result of Eq. (5) is shown for comparison. The simulated conductor loss has a peak around d of 0.8 μm and decreases steeply as d becomes less than 0.6 μm. Since the skin depth is about 0.3 μm at the given conductivity and frequency, this range corresponds to one in which d/δ

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is less than two. This tendency is also similar to the analytical result. Therefore, the surface currents on both sides of the electrode can be considered to overlap each other. However, the simulation results in the d/δ range of less than about 1.2 μm, slightly differ from the analytical ones. This may be caused by the multiple reflections between the surfaces of the electrode, which are not taken into account in the theory described in Sec. 2.

Next, we simulated the effect of reducing the conductivity σ, as another approach to decreasing d/δ. Figure 3 (c) shows the simulated conductor loss versus σ when d is 2.2 μm and the frequency is 60 GHz. Again, the analytical result of Eq. (5) is shown for comparison. The simulated conductor loss increases and then decreases in the direction of decreasing σ, or increasing skin depth. In particular, the conductor loss starts to decrease near 4×10^6 S/m. Since the skin depth is approximately 1 μm at this conductivity, the range of less than 4×10^6 S/m corresponds to the range in which d/δ is less than two. The analysis's tendency is the same as the simulation's. Thus, the surface currents having a thick skin depth on both sides of the electrode overlap and cancel each other, as they do in the case of decreasing the electrode thickness.

As a result, the method that we have presented can effectively reduce the conductor loss of the beam former.

4 Conclusions

By making the electrode thickness comparable with, or less than, the skin depth, the surface currents that flow on both sides of the electrode but in opposite directions cancel each other, resulting in a reduction of the conductor loss. EM simulations showing the quantitative effect of reducing the electrode thickness and decreasing the conductivity (increasing electrode skin depth) were carried out. As a result, it is shown that the above idea can effectively reduce the conductor loss. In particular, an attenuation constant of about 2 dB/m was obtained at an electrode thickness d of 0.2 μm in the case of using copper as the electrode material.

A Derivation of attenuation constant

The relation between power flow along a waveguide P, power loss P_l, and attenuation constant α is given by [7],

$$\alpha = \frac{P_l}{2P}. \tag{6}$$

The power flow P is derived as follows. The coordinates are defined as in Fig. 2. The electromagnetic field between the electrodes can be expressed as,

$$\boldsymbol{E} = E_x \boldsymbol{a}_x = A e^{-j\beta z} \boldsymbol{a}_x \tag{7}$$

$$\boldsymbol{H} = H_y \boldsymbol{a}_y = \tfrac{A}{\eta} e^{-j\beta z} \boldsymbol{a}_y, \tag{8}$$

where $\boldsymbol{a}_x$ and $\boldsymbol{a}_y$ denote the unit vectors of the coordinate system. The power flow P is given by the real part of the integral of the complex Poynting vector

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over the waveguide cross section. The width of the waveguide, or the length of electrode along y axis, is assumed to be of unit length, as mentioned in Sec. 2. Hence P is,

$$P = \frac{1}{2} Re \int_{-t}^{0} \boldsymbol{E} \times \boldsymbol{H}^* \cdot \boldsymbol{a}_z dx \;= \frac{tA^2}{2\eta}. \tag{9}$$

The power loss in the conductor per unit length P_l was derived as Eq. (4). By considering the tangential magnetic field represented by Eq. (8), the surface-current density at the surface of the electrode J_0 can be represented as follows.

$$J_0 = \frac{A}{\eta\delta}. \tag{10}$$

Substituting Eq. (10) into (4), we have

$$P_l = \frac{A^2}{\sigma\eta^2\delta}(1 - e^{-\frac{2d}{\delta}} - 2e^{-\frac{d}{\delta}}\sin(d/\delta)). \tag{11}$$

Finally we obtain the attenuation constant α_c by using Eq. (6) and substituting (9) and (11).

$$\alpha_c = \frac{P_l}{2P} = \frac{1}{\sigma\delta\eta t}(1 - e^{-\frac{2d}{\delta}} - 2e^{-\frac{d}{\delta}}\sin(d/\delta)). \tag{12}$$

B Estimation of leakge to adjacent LC layers

The leakage to adjacent LC layer was calculated in the case of d of $0.2\,\mu$m and σ of 5.8×10^7 S/m, which corresponds to d/δ of 0.74, by using the EM simulator. The simulation model is shown in Fig. 4. When the incident wave was fed only to the center LC layer, the power leakage to the adjacent LC layer was observed. As a result, a leakage to the adjacent LC layer of -19 dB was obtained.

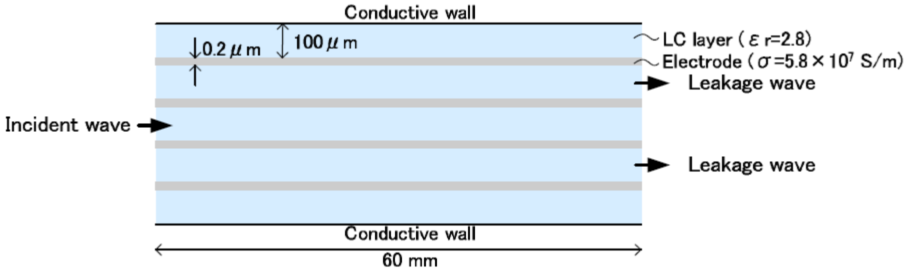

Fig. 4. Simulation model for leakage estimation. The LC layer thickness and the propagation length are the same as those of the previously fabricated beam former [1, 2] and were sufficient to control phase shifts of up to 360° at 60 GHz.

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