Design of Millimeter-Wave Transmitting Liquid Crystal Cells with Orthogonal Wire Grid Electrodes

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ABSTRACT

We propose a simple design scheme for orthogonally combined wire grid liquid crystal (LC) devices. In this scheme, the LC device is regarded as a combination of two wire grid polarizers. The fabricated device exhibited transmittance that was significantly larger than the aperture ratio, indicating anomalous transmission properties.

1 Introduction

Liquid crystal (LC) materials exhibit large birefringence not only in the visible region but also in the millimeter-wave (MMW) region. [1] By exploiting this feature, we can create various MMW-controllable LC devices [2] such as LC antennas that can receive and emit MMW in an arbitrary direction and intelligent reflecting surfaces (IRSs) that can change the reflection direction of MMW. These MMW devices have the potential to satisfy the practical and special demands of 5G/6G applications. An IRS is commonly used as a reflectarray antenna that can actively control the reflection of the incident MMW. In addition to this reflection-type device, the transmission-type MMW device may be a realistic option to satisfy the specific demand for MMW guide devices. For instance, typical large LC devices, such as smart windows and see-through-type digital signage devices, may interfere with MMW propagation from outside buildings (or rooms) to the inside owing to the low-resistance electrode films in the devices. Therefore, in smart windows and digital signage devices, high transmittance of the MMW is preferable.

Passive matrix LC devices can perform light-switching operations and may be used as smart windows. In addition, the device can be used for simple information display. The passive matrix is composed of orthogonally combined one-dimensional grid (wire grid) electrodes. [3] A well-designed orthogonal wire grid (OWG) reportedly exhibits a high transmittance of the MMW. [4] To increase the MMW transmittance in passive matrix LC devices while maintaining a large LC operation area, it is necessary to establish a design scheme for the device. In this paper, we propose a method for achieving high-MMW transmittance devices with a planned LC operation area.

2 Cell Structure and Fabrication

The investigated LC cell had the same sandwich structure as ordinary LC cells (Fig. 1). Indium tin oxide (ITO)/glass substrates have been used to realize light-controlling functions as smart windows. The ITO film was chemically etched to form striped patterns with the same electrode width and gap. Subsequently, the substrates were coated with polyimide (SE2170, Nissan Chemical) and unidirectionally rubbed in the direction of the electrode slit. Thereafter, the substrates were orthogonally combined to construct LC cells. Finally, the nematic LC, E7, was injected into it.

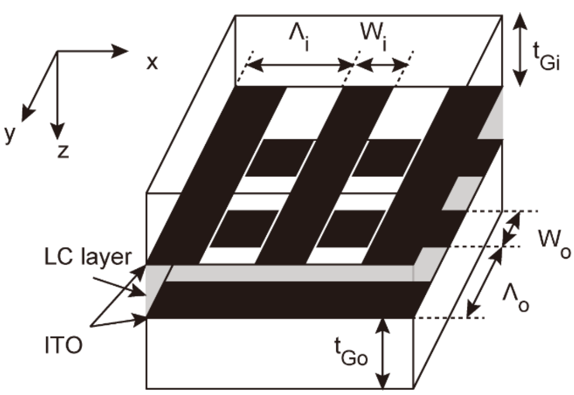

Fig. 1. Cross-sectional view of MMW-transmitting LC devices with the OWG electrode structure.

3 Design of MMW transparent LC cells

The investigated LC device was decomposed into two wire grid devices. Therefore, we started with the design of each wire grid instead of the entire LC device. It is known that an ordinary wire grid functions as a wideband linear polarizer. Thus, the orthogonal combination of two wire grids is called crossed polarizers. No MMW was transmitted through the OWG structure.

A perceptional change to overcome this problem is the effect of the substrate; that is, the glass substrate experiences multiple reflections. As a result, the transmitted MMW may significantly increase. To verify the validity of this idea, the influence of the glass substrate thickness, t_G, on the S-parameter of the wire grid was investigated. The calculation was conducted using the finite-difference time-domain method. The dielectric constant, ε', of the glass substrate was set at 6.76 ($\tan\delta$ = 0.025). The electrical conductivity of the electrode is assumed to be infinite. The period and electrode width of the wire grid were 1.8 and 0.9 mm, respectively. The design frequency was 70 GHz. The polarization direction of the incident MMW was perpendicular to the electrode slit (the *x* direction in Fig. 1).

As shown in Fig. 2, the transmittance S_{21} is significantly greater than reflectance S_{11} in the case without the glass substrate (t_G = 0 mm). However, the characteristics changed drastically with the addition of the glass substrate. As shown in Fig. 2, the transmittance is significantly reduced, and the reflectance is increased at the design frequency (70 GHz). This reversal phenomenon was also observed when the polarization direction was parallel to the electrode slit.

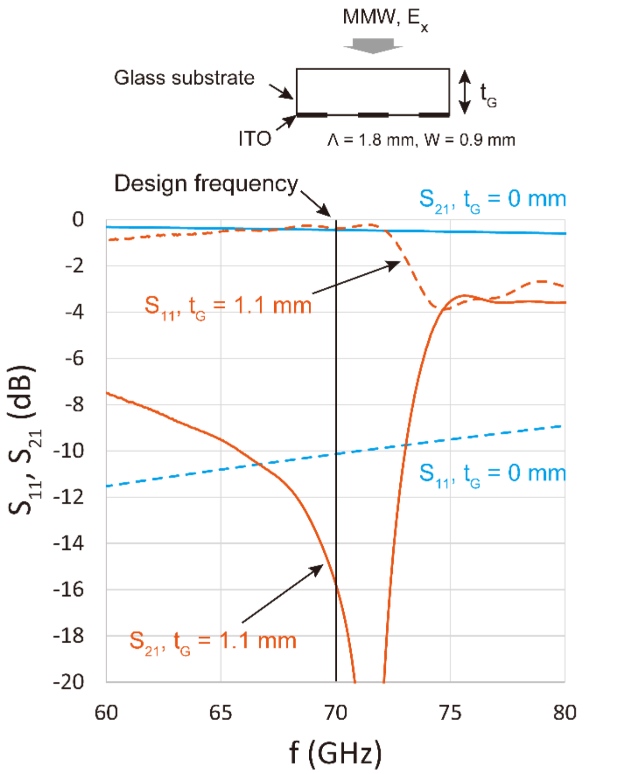

Fig. 2. Reflection and transmission properties of a wire grid where the grid period is 1.8 mm and width is 0.9 mm. The term t_G denotes the thickness of the glass substrate. The polarization direction is perpendicular to the electrode slit.

When the substrate thickness was appropriately adjusted, the wire grid on the substrate exhibited reverse characteristics. By utilizing this feature, we can achieve “parallel polarizers” even when two wire grids are orthogonally combined. Figure 3 shows the reflection and transmission properties of the OWG LC device, where the input- and output-side wire grids operate in normal and reverse modes, respectively. In Fig. 3, the terms E_x and E_y indicate that the polarization direction of the incident MMW is perpendicular (or parallel) to the input-side electrode slit.

As illustrated in Fig. 3, in the case of E_x, the transmittance coefficient (0.93) was significantly greater than the reflectance coefficient (0.051) at the design frequency (70 GHz). However, the reflectance exceeded the transmittance in the case of E_y.

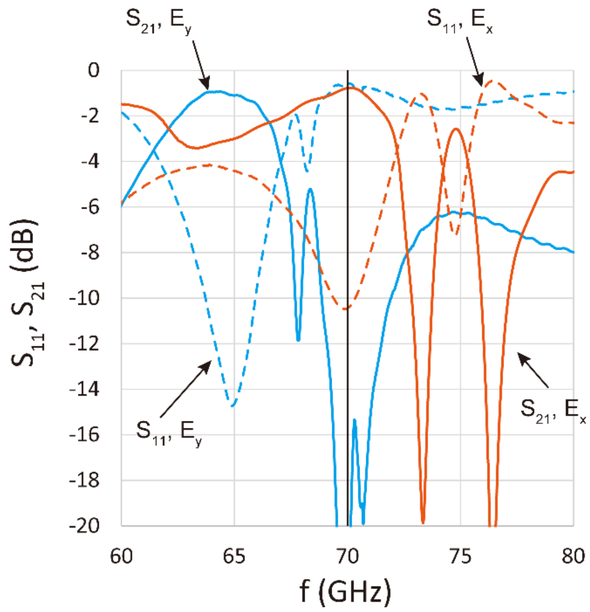

Fig. 3. Reflection and transmission properties of the OWG devices shown in Fig. 1 (Λ_i = 1, W_i = 0.5, Λ_o = 1.8, W_o = 0.9, t_{Gi} = 1.3, t_{Go} = 1.1, and t_{LC} = 0.02 mm). The terms E_x and E_y denote that the polarization direction is parallel to the *x*- and *y*-axes, respectively.

Step 1

Set the values of the grid period, Λ_i and Λ_o, electrode width, W_i and W_o, LC layer thickness, t_{LC}, frequency, *f*, and polarization direction (*x* or *y*).

Step 2a

Determine (tentatively) the substrate thickness, t'_{Gi}, so that the transmittance of the input side substrate become maximum.

Step 2b

Determine (tentatively) the substrate thickness, t'_{Go}, so that the transmittance of the output side substrate become maximum.

Step 3

Adjust and determine the substrate thickness, t_{Gi} and t_{Go}, so that the transmittance of the constructed LC cell become maximum.

Fig. 4. Proposed design scheme.

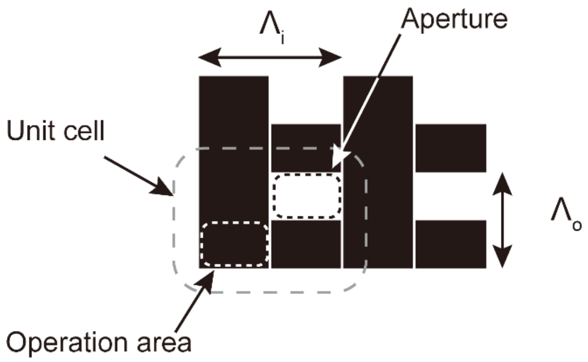

Fig. 5. Definition of the aperture and operation area.

Based on the above discussion, we propose a design scheme of the substrate thickness as shown in Fig. 4. As shown in Fig. 3, we fabricated OWG devices with similar parameter values, except for the glass substrate thicknesses t_{Gi} and t_{Go}. These thicknesses cannot be set as arbitrary values in actual experiments. Hence, we varied t_{Gi} and t_{Go} by stacking cover glass plates (approximately 0.15 mm) on a regular glass substrate (0.7 mm thick). Consequently, a relatively high transmittance of 0.55 was obtained when the polarization direction was parallel to the *x*-axis. The transmittance is proportional to the aperture ratio, R, which is defined as $R = (\Lambda_i - W_i)(\Lambda_o - W_o)$ (see Fig. 5). For the fabricated device, $R = 0.25$. Notably, the obtained transmittance of 0.55 was significantly greater than the aperture ratio of 0.25, suggesting anomalous transmission properties.

4 Conclusions

In this paper, we proposed a simple design scheme for the OWG LC devices. The essence of the design scheme is that the OWG device can be regarded as a combination of two wire grids that can be designed separately to maximize the MMW transmittance. A prototype OWG device was fabricated to validate the proposed scheme. As a result, a high transmittance of 0.55 was obtained although the aperture ratio was 0.25.

References

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