Focusing Properties of Liquid Crystal Lens Cells With Stack-Layered Structure in the Millimeter-Wave Region

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***Abstract*—Liquid crystal (LC) lens cells are fabricated using a nematic LC material with a positive dielectric anisotropy and semicircle-shaped metal substrates as quasioptical millimeter-wave devices. The millimeter-wave focusing properties of the LC lens are measured at 94 GHz and its convergent effects caused by the lens-shaped configuration are then observed. Changes in the focusing properties by applying the external electric field are confirmed.**

***Index Terms*—Lens, liquid crystal, millimeter wave.**

I. Introduction

Large electro-optic effects of nematic liquid crystal (LC) materials that can easily be controlled by an external electric field are widely used in displays and optical devices. Other potential applications include electrically controlled devices in the longer wavelength region such as the infrared (IR), submillimeter-wave, millimeter-wave, and microwave region. Relatively large birefringence with low loss of LC materials in the IR region is expected [1] and many studies on LC devices in the optical fiber communication system have already been reported [2], [3]. The refractive index and loss parameter of some nematic LC materials as the optical properties in the submillimeter-wave region are investigated and a large birefringence comparable with the visible region are confirmed [4]. LC materials also have relatively large dielectric anisotropy in the millimeter-wave and microwave regions and electrically or magnetically controlled devices such as phase shifters [5], [6] and delay line [7] have been reported.

There have been many studies on millimeter-wave application systems in the field of communication and radar systems. Millimeter-wave bands require only small size equipment compared to radio wave frequencies. Quasioptical techniques provide a very useful means for development of the microwave and millimeter-wave devices because of the inherent ease of fabricating and handling large size devices compared with the wavelength.

As devices with modulation effects, LC materials having the above-described features are applicable to quasioptical millimeter-wave devices. The LC lens [8] in the visible wavelength region is composed of the LC and a lens-shaped substrate with an electrode to drive the LC molecules. The focusing properties can be varied by applying an external electric field. LC cells having a stack-layered structure that have large modulation effects in the millimeter-wave region were fabricated in a previous study [9]. This paper proposes an LC lens with the stack-layered structure as quasioptical millimeter-wave devices and measures the focusing properties at 94 GHz.

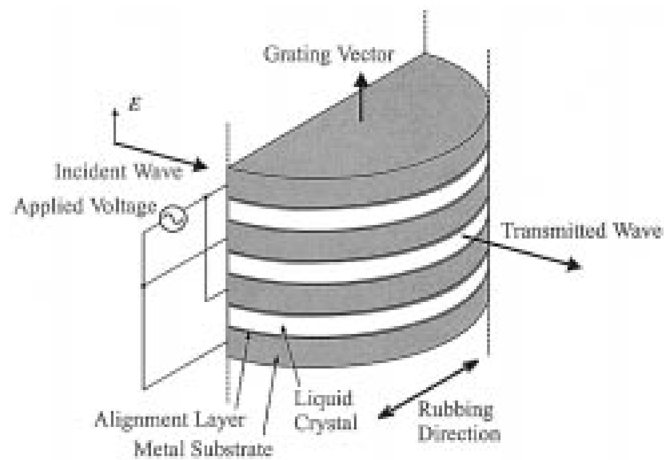

Fig. 1. Structure of liquid crystal lens with metal substrates.

II. Experiment

Homogeneously aligned cylindrical LC lens cells with the stack-layered structure, as shown in Fig. 1, were prepared using the nematic LC (E44) with positive dielectric anisotropy and the metal substrates. The nematic LC was put into the cell fabricated from a pair of semicircle-shaped metal substrates. The thickness of the LC layer was controlled by a 300 μm glass ball spacer. The thickness and the radius of the semicircle-shaped metal substrates were 1 mm and 25 mm, respectively. The metal substrate was coated with polyvinyl alcohol (PVA) film and rubbed to achieve a homogeneous molecular orientation. The experimental system for measuring the millimeter-wave transmission pattern is shown in Fig. 2. The millimeter wave supplied by a Gunn diode is radiated from a transmitting horn antenna. The operating frequency is 94 GHz. Then, the wave is normally incident on the LC cell which is set with an aperture of $D = 40$ mm. The transmitted wave is received by an open-ended W-band rectangular waveguide (internal dimension 2.54×1.27 mm) and is detected by a diode. The waveguide antenna with the detector can be swung around the LC cell to measure the millimeter-wave diffraction pattern. The grating vector

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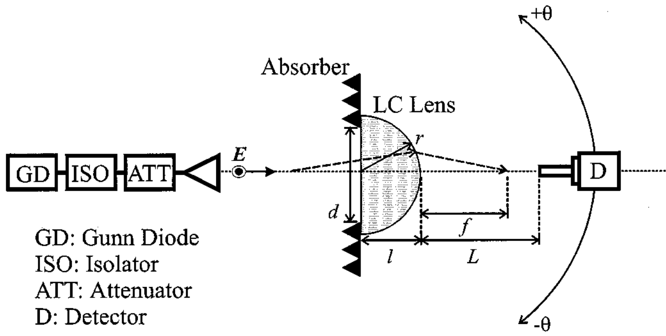


Fig. 2. Experimental setup.

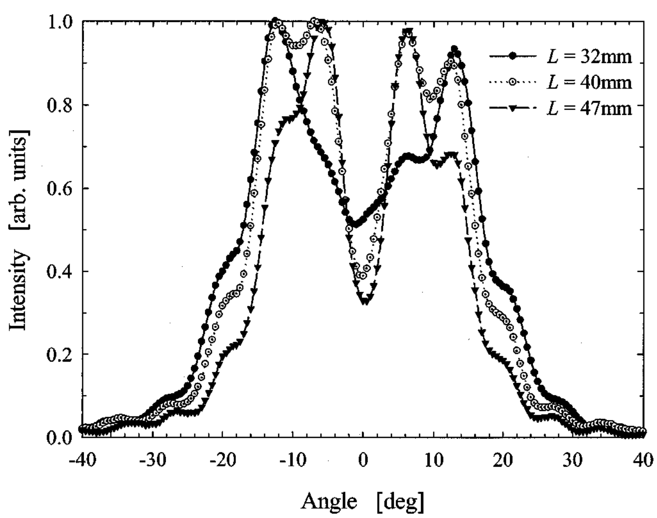
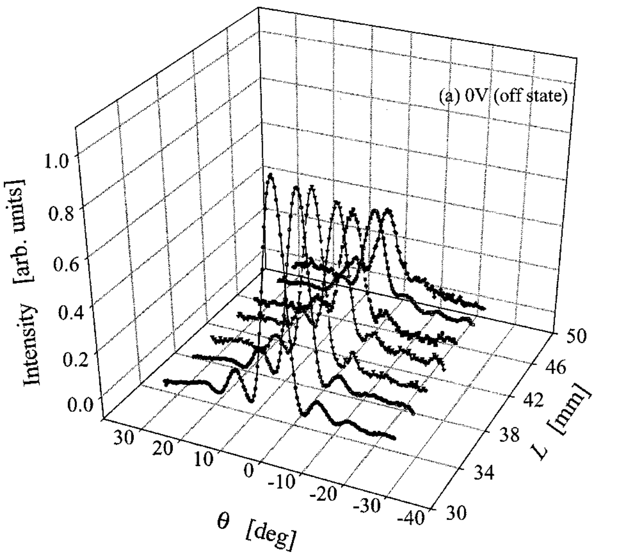


Fig. 3. Measured millimeter-wave diffraction pattern without the LC cell.

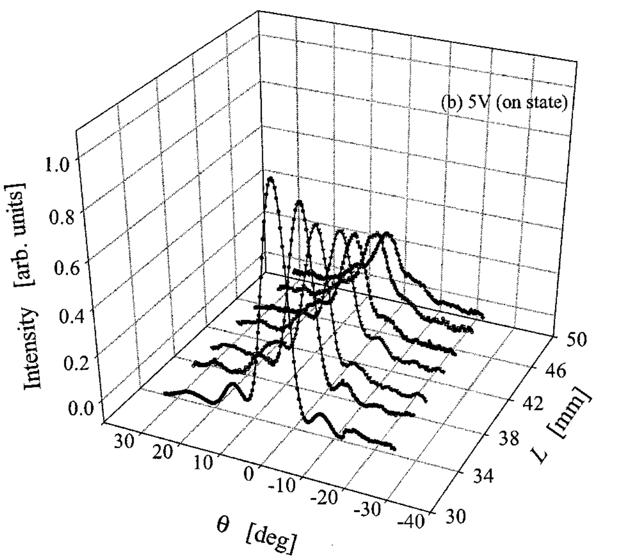
of the stack-layered structure is parallel to the polarization direction of the millimeter wave since the propagating wavelength is longer than the cutoff wavelength determined by the spacing of the metal substrates. The effective refractive index of the LC layer is $n_{\perp}(=\varepsilon'_{\perp}{}^{1/2})$, since the director of LC aligns parallel to the substrates in the off state. The LC cell is driven by a 1 kHz sinusoidal ac voltage. When the voltage is applied across the LC layer (on state), the LC director is reoriented toward the direction parallel to the millimeter-wave electric field and thus the effective refractive index of the LC layer changes to $n_{/\!/}(=\varepsilon'_{/\!/}{}^{1/2})$. The values of $\varepsilon'_{\perp}=2.5$ and $\varepsilon'_{/\!/}=3.0$ were used as the permittivities of the LC for the ordinary and extraordinary waves at the 90 GHz band [9]. The calculated focal lengths of the ray passing through the vicinity of the center of the aperture for the off state and on state become about 43 mm and 34 mm, respectively. All measurements were carried out at room temperature.

III. Results and Discussion

The millimeter-wave focusing properties of the LC lens were measured for various distances L between the LC lens and the receiving antenna. Fig. 3 shows the diffraction patterns of the millimeter wave without the LC lens as a function of the angle θ, where the millimeter-wave intensities are normalized against the maximum intensity. The transmitted wave from the aperture is diffracted with an angle range of about $\pm 30^{\circ}$ and the Fresnel diffraction pattern is observed due to the short distance between the aperture and the receiving antenna. Fig. 4(a) and (b) show the radiation field patterns of the wave with the LC lens at the off state and the on state, respectively. Fig. 4(a) shows that the wave through the LC lens is focused at an angle of about $\pm 15^{\circ}$ including the side lobe and the Fraunhofer diffraction pattern observed near the focal point. The main lobe width of the focused millimeter wave is about 12°. This value is close to the diffraction limit of 9.2° calculated using the relationship between the wavelength and the aperture width $2\tan^{-1}(\lambda/D)$. When a voltage of 5 V is applied to the LC lens, the diffraction pattern becomes defocused near the distance of about 45 mm, as shown in Fig. 4(b), compared to the off state. The application of the voltage shifts the focal position toward a shorter position causing the millimeter wave to diverge.



(a)



(b)

Fig. 4. Measured millimeter-wave diffraction pattern with the LC lens. (a) Off state and (b) on state.

Fig. 5 shows the change of full width at half maximum (FWHM) of the millimeter-wave diffraction pattern as a function of applied voltage. FWHM increases as the voltage

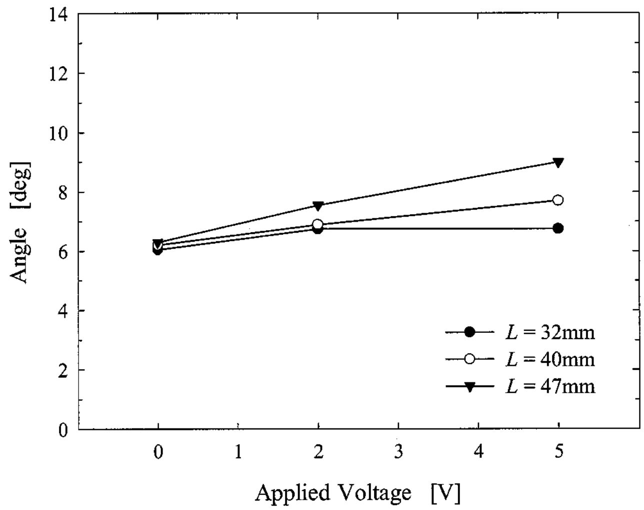
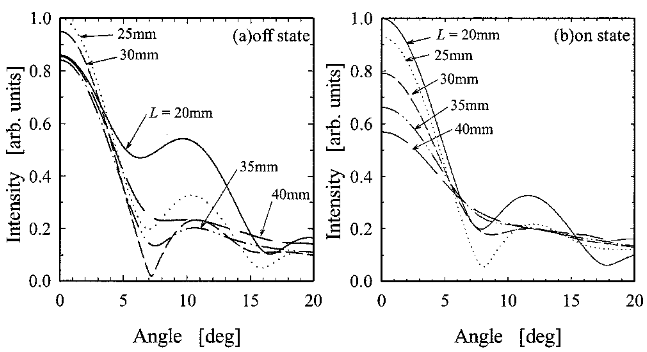


Fig. 5. Change in FWHM of diffraction patterns as a function of applied voltage.



(a) (b)

Fig. 6. Calculated millimeter-wave diffraction pattern with the LC lens. (a) Off state and (b) on state.

increases. Each FWHM is about 6° when no voltage is applied to the LC lens. FWHM for $L = 47$ mm becomes large when the voltage is applied to the LC lens because of the defocusing effect of the LC lens. It is difficult to determine the focal length of the LC lens clearly in the experiment, since the diffraction limit and the spherical aberration caused by the semicircle-shaped LC lens with the small effective aperture width are remarkable.

The finite-difference time-domain (FDTD) calculation was carried out to investigate the focusing properties of the LC lens. Fig. 6(a) and (b) show the calculated millimeter-wave field patterns of the LC lens for various distances L at the off state and the on state, respectively, where the intensities are normalized against the maximum intensity. As shown in Fig. 6(a), the focal position is expected to be exist near the distance of about 25 mm for the off state. The main lobe width of the focused millimeter wave is estimated to be about 14°. For the on state [Fig. 6(b)], the millimeter wave is certainly defocused as the distance L increases.

IV. Conclusion

This paper proposes a stack-layered LC lens consisting of the nematic LC and semicircle-shaped metal substrates and investigates the millimeter-wave focusing properties. The millimeter wave can be converged and the Fraunhofer diffraction pattern is obtained near the focal point by using this cylindrical lens-shaped LC cell. In addition, changes in the focusing properties of the LC lens are observed when the external electric field is applied to the LC lens. Since the focusing properties of the LC lens depend on the effective aperture width and curvature of the lens, the optimization of these parameters are necessary for the electrically controlled LC lens with good focusing properties.

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