

# A millimeter-wave quasi-optical grid phase shifter using liquid crystal

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**Abstract:** A new type of millimeter-wave quasi-optical variable phase shifter which exploits the dielectric anisotropy of liquid crystal (LC) materials is presented. The device is operated in transmission mode and consists of inductive and capacitive metal grids, each patterned on a dielectric substrate, which are separated by a thin layer of LC. The grids together with the LC form a parallel resonant circuit. Prototype devices with a 25- $\mu\text{m}$ -thick LC layer for use at a millimeter-wave frequency of 50 GHz were designed and fabricated. Experiments performed at U-band frequencies show that a phase shift of  $7.8^\circ$  is obtained with a low insertion loss of  $\sim 0.6$  dB at the resonant frequency by applying a control signal of 20 V. Good time response for the device is demonstrated. It is suggested that the phase shift attainable with the device can be further enhanced by using LC materials with larger dielectric anisotropy and/or thinner dielectric substrates.

**Keywords:** grid structures, liquid crystals, millimeter wave, phase shifters, quasi optics

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

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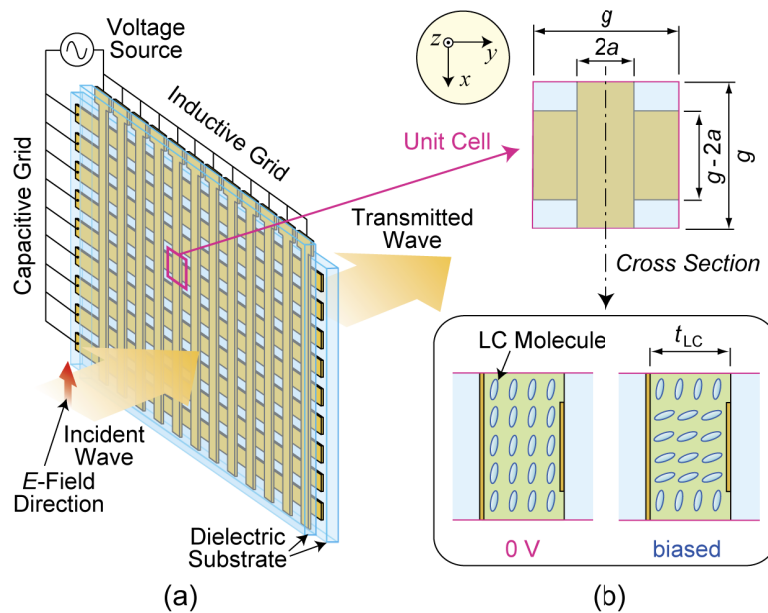
## 1 Introduction

Recent advances in microwave and millimeter-wave devices which exploit the dielectric anisotropy of liquid crystal (LC) materials have mainly been accomplished using planar waveguide structures [1, 2] and quasi-optical structures [3, 4, 5]. In the former, a microstrip delay line using dual-frequency switching mode LC [1] and a microstrip phase shifter using polymer-dispersed LC [2] have been developed to improve insertion loss and time response. Quasi-optical devices utilizing LC materials have been proposed to realize reconfigurable optics [3, 4] and to generate an electronically tunable band-pass filter [5].

Here, we propose a novel type of quasi-optical variable phase shifter using LC material that incorporates the traditional grid structures [6]. The device configuration is presented in the next section, followed by the design and fabrication of the device. Experimental results performed at U-band frequencies to measure the basic characteristics of the device are presented.

## 2 Device configuration

Fig. 1 shows a schematic drawing of the quasi-optical grid phase shifter using LC material. A thin layer of LC material is sandwiched between an inductive and its complementary capacitive metal grid. Each grid is patterned on a dielectric substrate. The strips of the inductive grid are electrically connected in parallel, as well as the strips of the capacitive grid. A voltage is applied between the inductive and capacitive grids to control the direction of the LC molecules in the crossed regions between the strips, as depicted in Fig. 1(b). The permittivity of the crossed regions varies between two values,  $\varepsilon_{//}$  (parallel orientation relative to the RF electric field) and  $\varepsilon_{\perp}$  (perpendicular orientation), and the dielectric tunability of the LC is defined as

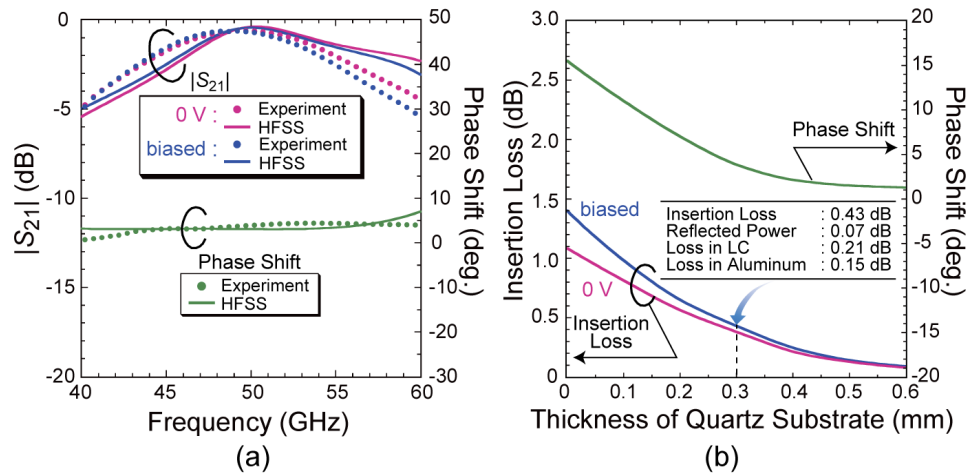


**Fig. 1.** Schematic plot of millimeter-wave quasi-optical grid phase shifter using liquid crystal. (a) device structure, (b) unit cell representing one period of the whole structure.

$\Delta\epsilon = \epsilon_{//} - \epsilon_{\perp}$ . The incident wave is linearly polarized with the electric field ( $E$ -field) direction parallel to the strips of the inductive grid. Because the inductive and capacitive grids are evanescent-wave devices and are treated as inductive ( $L$ ) and capacitive ( $C$ ) elements [6], respectively, the grids separated by the thin LC layer can be modeled as a parallel resonant circuit. At the resonant frequency, the intensity of the transmitted wave through the device is maximized. When changing the dielectric properties of the LC layer by applying a control voltage, the capacitance of the resonant circuit changes, resulting in a shift of resonant frequency, and hence phase shifting of the transmitted wave arises. Since the phase change is rapid around resonance, enhancement of the phase agility is expected even with a thin layer of LC. We found in the HFSS simulation described in the next section that an intense  $z$ -direction  $E$ -field is excited by the incident millimeter-wave in the crossed regions between the strips. This  $E$ -field can interact with the direction-controlled LC molecules, leading to a change in the capacitance.

### 3 Design and fabrication

The quasi-optical grid phase shifter was designed to operate at a millimeter-wave frequency of 50 GHz using the Ansoft High-Frequency Structure Simulator (HFSS). A unit cell, shown in Fig. 1(b), representing one period of the whole periodic structure was simulated [7]. The LC material assumed in the simulation is K15 (Merck). The permittivities ( $\epsilon_{//} = 2.92$ ,  $\epsilon_{\perp} = 2.62$ ) and loss tangents ( $\tan \delta_{//} = 0.01$ ,  $\tan \delta_{\perp} = 0.02$ ) corresponding to the two molecular orientations of K15 measured at 50 GHz [8] were used. The thickness of the LC layer,  $t_{LC}$  in Fig. 1(b), is 25  $\mu\text{m}$ . As far as we know, this is the



**Fig. 2.** Comparison of calculated and measured results of the transmission coefficient and phase shift as a function of frequency (a), and calculated insertion loss and phase shift at 50 GHz as a function of thickness of the quartz substrate. The calculated material losses and reflected power forming the insertion loss when the thickness is 0.3 mm under biased conditions is shown in the inset table in (b).

thinnest LC layer employed in microwave and millimeter-wave devices using LC reported so far. Since the time response of LC devices can be improved by using thinner LC layers [2], good time response for the device is expected. The grid period,  $g$ , was selected as 2 mm in order to prevent higher-order diffraction [6]. As the dielectric substrates for the device, we selected fused quartz substrates, which have a relatively low permittivity value of 3.78 and negligible loss.

Fig. 2(a) shows the calculated transmission coefficient,  $|S_{21}|$ , and phase shift as a function of frequency at U-band frequencies (40–60 GHz). The measured results are also shown, which are explained in the next section. The widths of the inductive grid,  $2a$ , and the capacitive grid,  $g - 2a$ , are 0.70 mm and 1.30 mm, respectively. The material of the grids is aluminum, and their thickness is 1  $\mu\text{m}$ . The quartz substrates are both 0.3 mm thick. The resonant curve for  $|S_{21}|$  shown in Fig. 2(a) is shifted to lower frequencies, when the LC layer is biased. The phase shift is calculated by subtracting the phase of  $S_{21}$  when the LC layer is biased from that when unbiased (0 V). A phase shift of  $3.8^\circ$  is expected at 50 GHz.

Fig. 2(b) shows the calculated insertion loss and phase shift at 50 GHz as a function of the thickness of the quartz substrate. The inset table shows the calculated individual loss values (reflected power, and material losses in the LC and the aluminum strips) forming the insertion loss for the 0.3-mm-thick quartz substrate when the device is biased. The design parameter,  $a$ , is adjusted in order to maximize the transmission at 50 GHz when the LC layer is unbiased. As the quartz substrate becomes thinner, the intensity of the  $z$ -

direction  $E$ -field in the crossed regions between the inductive and capacitive strips increases, resulting in enhancement of the effect of the permittivity change of the LC layer on the capacitance of the capacitive grid, and hence in an increase in the phase shift, while this increase in the  $E$ -field intensity also leads to a rise in the material loss [6]. The loss in the LC layer is the largest component of the insertion loss. Although the phase shift is improved using thinner quartz substrates, for ease of fabrication for the prototype device, we selected 0.3-mm-thick quartz substrates for the device to be fabricated.

A quasi-optical grid phase shifter using K15 with a 70-mm-square clear aperture was fabricated. A pair of quartz substrates, each having an inductive and a capacitive grid patterned using a conventional photolithographic technique, were coated with polyvinyl alcohol (PVA) film and rubbed to achieve homogeneous LC molecular orientation. The thickness of the LC layer was controlled by glass ball spacers ( $25\text{ }\mu\text{m}$  in diameter). Another phase shifter using a different LC material, BL006 (Merck), which has a larger dielectric tunability and a larger viscosity than K15 [2], was also fabricated for comparison. These two kinds of phase shifter were made with the same design parameters, except the LC material.

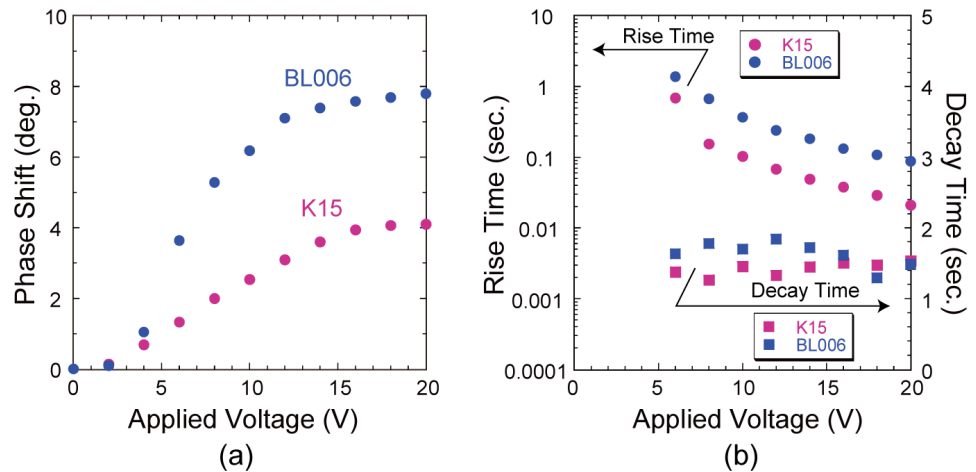
#### 4 Experimental results and discussion

Experiments were performed at U-band frequencies (40–60 GHz) using a quasi-optical measurement system. In the experiment, the devices were driven with a 1 kHz sinusoidal ac voltage. The measured results of  $|S_{21}|$  and the phase shift with a bias voltage of 20 V (peak to peak) for the device using K15 are plotted in Fig. 2(a), showing good agreement with the calculated ones. The measured insertion losses at 50 GHz when the device is biased and unbiased are 0.63 dB and 0.61 dB, respectively.

Fig. 3(a) shows the phase shift at 50 GHz as a function of applied voltage for the devices using K15 and BL006. The phase shift becomes larger and then constant as the voltage is increased. Phase shifts of  $4.1^\circ$  for K15 and  $7.8^\circ$  (0.64 dB and 0.63 dB insertion losses for the biased and unbiased conditions, respectively) for BL006 were obtained, demonstrating larger phase shifts by LC materials with larger dielectric tunability.

Fig. 3(b) shows the measured 10 to 90% rise time and the 90 to 10% decay time of the devices. The rise time becomes smaller as the applied voltage increases, while the decay time remains constant ( $\sim 1.5\text{ s}$ ). The rise times of the devices using K15 and BL006 at an applied voltage of 20 V are 20 ms and 90 ms, respectively. These response times are equivalent or smaller than the reported results so far [1, 2] at the same applied voltage. The results shown in Fig. 3 well reflect the difference of the physical properties of these two LC materials.

As shown in Fig. 2(b), a phase shift of up to  $15.5^\circ$  can be obtained with the K15 device by employing thinner quartz substrates. As demonstrated, further improvement of the phase shift is possible by using LC materials with larger dielectric tunability. Recently, a novel LC material has been



**Fig. 3.** Measured phase shift (a) and response times (b) as a function of applied voltage for two kinds of phase shifter using K15 and BL006.

developed, having about three times higher tunability and lower losses compared to K15 [9]. We found in the HFSS simulation, using the permittivities ( $\epsilon_{//} = 3.13$ ,  $\epsilon_{\perp} = 2.26$ ) and loss tangents ( $\tan \delta_{//} = 0.004$ ,  $\tan \delta_{\perp} = 0.0125$ ) of this new LC material [9], that a phase shift of up to  $46.7^{\circ}$  (2.50 dB and 0.91 dB insertion losses for the biased and unbiased conditions, respectively) is expected. This phase agility is promising for the proposed quasi-optical phase shifter used in millimeter-wave applications where fast phase shifting is needed. Finally we should point out that the phase shifter proposed herein has the potential to achieve beam steering when the two-dimensionally arranged active LC layers are unevenly biased.

## 5 Conclusion

We proposed and fabricated a new type of millimeter-wave quasi-optical variable phase shifter which exploits the dielectric anisotropy of liquid crystal materials. The phase shifter was designed to operate at a millimeter-wave frequency of 50 GHz, and phase shifts of  $4.1^{\circ}$  and  $7.8^{\circ}$  with low insertion loss ( $\sim 0.6$  dB) were demonstrated for two types of LC material. Good response times for the devices were obtained. It is suggested that the phase agility of the device can be further enhanced by utilizing LC materials with larger dielectric anisotropy and/or thinner quartz substrates.

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