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RESEARCH PAPER

Reflowable liquid crystal geometric phase element for vertical cavity surface emitting laser projector

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ABSTRACT. We proposed a reflowable liquid crystal (LC) geometric phase element for vertical cavity surface emitting laser (VCSEL) projector. By photo alignment technology and LC one drop fill process, we realized an active LC geometric phase element and pattern switchable VCSEL projector. According to geometric phase distribution, the incident light was transformed into different light distribution, such as flood pattern, beam multiplication, or wider illumination. When voltage was applied, all LC directors aligned perpendicularly to substrates and the geometric phase distribution vanished. Therefore, the output light remained as the original projecting pattern. Due to narrow wavelength range of the VCSEL, the optical performance, such as diffraction efficiency and phase difference, was not decayed by the dispersion of geometric phase. We made a record of 3×3 mm LC cell with our in-house ink-jet printing system. The transmittance was over 95%, and the switching time was <5 ms.

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1 Introduction

Vertical cavity surface emitting laser (VCSEL) features in the properties of high speed operation, low power consumption, and small volume. The features make VCSEL suitable for 3D sensing applications.[1–5] Since 2017, iPhone X produced by Apple adopted structure light for facial recognition, and VCSEL were widely used in the 3D depth sensing in the mobile market.

For mobile applications, one VCSEL projector unit with fixed light pattern may not satisfy the function. For example, the structured light 3D sensing includes a flood illuminator and a dot projector. Flood illuminator is for capturing 2D images and checking if a face exists or not. Dot projector is for creating a digital 3D map. Furthermore, the application requires to increase dot numbers to enhance 3D resolution or wider illuminated angles to capture wider 3D information. For these scenarios, multiple independent pattern illuminators are necessary, which inevitably raises the footprint and cost comparing to single illuminator.

For reducing illuminator numbers, we can utilize light pattern switching devices. Due to the electrically tunable properties, liquid crystal (LC) is an excellent candidate to achieve it. For example, volume scattering-based LC diffusers, such as polymer dispersed LCs, polymer stabilized LCs (PSLCs), and polymer network LCs, can scatter dot pattern into flood pattern.[6] However, scattering type device scatters light in forward and backward directions simultaneously, which causes significant drop in optical efficiency. On the other hand, tunable micro lens or gratings, which converge or steer the incident light, can be realized by carefully manipulating

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LC directors and effective refractive index distribution. However, polarization dependency of LC effective refractive index may need extra polarizers to confine the polarization of light source.

In this paper, we demonstrate VCSEL projector light pattern switchable LC devices based on photo alignment technology. According to geometric phase theory, we created an LC alignment distribution that diffuses or steered the light passed through the device. When we applied voltage to the LC device, all LC directors rotate to be normal to substrates and the geometric phase distribution is vanished. The light pattern remains the same after it passes through the LC device. Since the light pattern modulation is based on geometric phase distribution, back scattering effect can be ignored. The optical efficiency is high as >95%. Besides, the polarization of incident light could be an arbitrary direction of linear polarized light or unpolarized light. The LC device is reflowable, and total switching time is <5 ms.

2 Operating Principles

Geometric phase is based on the phase shift generated when circular polarized light encounters a half wave retarder. The phase shift depends on the azimuthal angle of the half wave retarder. Also, orthogonal circular polarized lights encounter opposite phase shift.[7] By designing an azimuthal angle distribution of retarder, the element provides a phase shift distribution to the incident light. Theoretically, when the phase retardation of the element is half wavelength, it reaches 100% diffraction efficiency. With the birefringence of LC, geometric phase can be realized by LC. The relation between first-order diffraction efficiency and phase retardation of LC cell is shown below:[8,9]

$$\eta_{\pm 1} = \sin^2\left(\frac{\pi \Delta n d}{\lambda}\right), \tag{1}$$

Δn is the birefringence of LC materials; d is the thickness of LC layer; and λ is the wavelength of incident light. When angle of incident light increases, effective LC layer thickness d will increase and effective birefringence of LC will decrease. For the application where the incident angle is <30 degree, the diffraction efficiency difference will not exceed 10% for different incident angles. In some applications, we may design the first-order diffraction efficiency to be low. With different geometric phase distribution and diffraction efficiency design, we can achieve different light pattern modulation for VCSEL. For example, it can be steering, pattern multiplying, diffusing, and focusing, as shown in Fig. 1.

Combining with dot projector and sensors, we realized a 3D sensing module prototype with two-in-one pattern projector, as shown in Fig. 2. The projection light can be switched between dot and flood pattern for different image sensing function. It is the first active geometric phase element to apply on the consumer product.

3 Fabrication of LC Geometric Phase Elements

Photoalignment is the key technology to realize geometric phase LC alignment. According to prior art,[10] a grating pattern illumination is required to create LC geometric phase. First, we setup an interferometer[11,12] to create grating pattern on photoalignment layer on glass. We use two-mirror Sagnac interferometer with 10 cm focal length template lens to create lens pattern and conventional polarization holography setup to fabricate grating pattern. Then, we coated and cured LC polymers with half wavelength phase retardation for 365 nm on the photoalignment

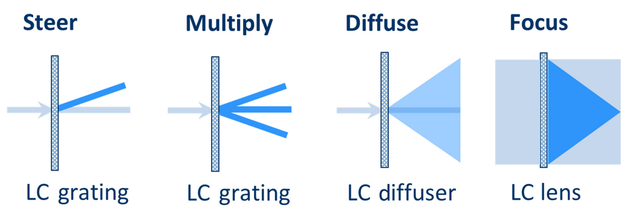

Fig. 1 LC geometric phase elements with different phase distribution and functions for VCSEL projector.

Fig. 2 3D sensing module prototype with two-in-one pattern projector.

layer to create a geometric phase mask. Second, we shined collimated and linear polarized 365 nm light through geometric phase mask to an index-matched ITO glass coated with photo-alignment layer. The process built an alignment direction grating pattern with half grating period on the glass substrate. By LC one drop fill (ODF) process, we finished the switchable LC element fabrication. The birefringence of LC is ∼0.235 for 940 nm. The cell gap of LC was ∼2 μm and the phase retardation of LC was half wavelength for 940 nm when voltage is off. By design of patterning ITO and conducting ball, two electrode pads were on the same glass substrates. It could apply wire-bonding or FPC bonding for driving. The dimension of LC diffuser was 5 mm × 6 mm × 0.42 mm and the active area was 3 mm × 3 mm.

4 Experimental Results

We achieved three different types of LC geometric phase element for 940 nm VCSEL projector. They were LC diffuser, LC beam multiplier, and LC angular extender.

4.1 LC Diffuser

The dot size and dot separation from the VCSEL dot projector were 0.25 deg and 0.88 deg. We designed micro lens arrays (MLAs) geometric phase pattern of the LC diffuser. The diameter of single lens was 400 μm and the lens power was 360 diopters. The polarized optical microscope (POM) observation of LC diffuser under cross polarizer with green light source is shown as Fig. 3. The diffusing angle is around 8 deg and the dot separation from VCSEL is 0.88 deg, therefore, the diffusing light from each dot pattern can overlap well with others and get uniform

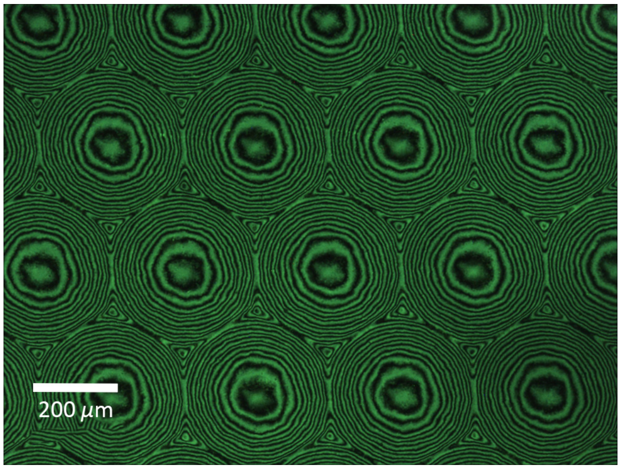

Fig. 3 The POM observation of LC diffuser under cross polarizer with green light source.[10]

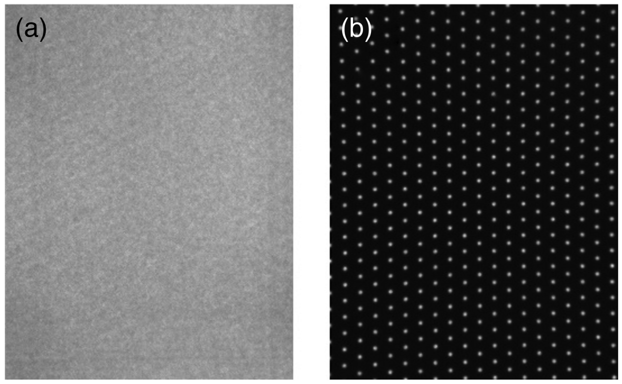

Fig. 4 The projected pattern by switchable VCSEL dot projector with LC diffuser.[10] (a) Flood pattern when LC diffuser is voltage off. (b) Dot pattern when LC diffuser is voltage on. The screen is 70 cm away from LC diffuser.

Table 1 Measuring results of LC diffuser. Average of measuring results of 15 samples.

Item	Before baking test	After baking test
Flood contrast	1.48	1.44
Dot contrast	22.16	22.23
Voltage off transmittance	95.2%	95.1%
Voltage on transmittance	96.0%	96.1%
Total switching time	4.43 ms	4.14 ms

flood pattern. The projected light on a screen 70 cm away were shown as Fig. 4. The flood contrast was <2 and dot contrast was >22. Flood contrast performed the uniformity of flood illumination. The performance is acceptable for flood illuminator. The LC diffusor could replace the dot projector and flood illuminator function for 3D recognitions. The total switching time ($t_{on} + t_{off}$) is <5 ms and the transmittance is >95%.[5]

Reflow soldering is a preferred and widely used method of soldering surface mount technology components to a printed circuit board. The highest temperature of reflow process is ~250°C and maintains $10 \sim 18$ s. The process should be repeat two to five times. We baked LC diffusers in oven with 260°C in 5 min for reflow ability test. Then, we compared contrast, transmittance, and switching time before and after oven baking. The measuring results were shown in Table 1. There was no significant performance change after the reflow ability test.

4.2 LC Beam Multiplier

We used the same VCSEL dot projectors as LC diffuser demonstration to realize beam multiplication. We designed grating geometric phase pattern of the LC beam multiplier. The grating pitch was 122 μm in one fixed direction. The projected light on screen 70 cm away were shown as Fig. 5. According to Eq. (1), we applied a voltage to achieve quarter wavelength phase retardation and satisfy the diffraction efficiency ~50%. Therefore, projected light intensity of 0 order was twice of $+1$ order and -1 order. Due to one of the $+1$ order dot was overlapping with the adjacent -1 order dot, the light intensity for every dot after beam multiplying was consistent and the dot separation turned into 0.44 deg.

4.3 LC Angular Extender

A VCSEL flood illuminator with 18 deg × 22 deg illumination angle was used for demonstration. We designed grating geometric phase pattern of the LC angular extender. The grating pitch

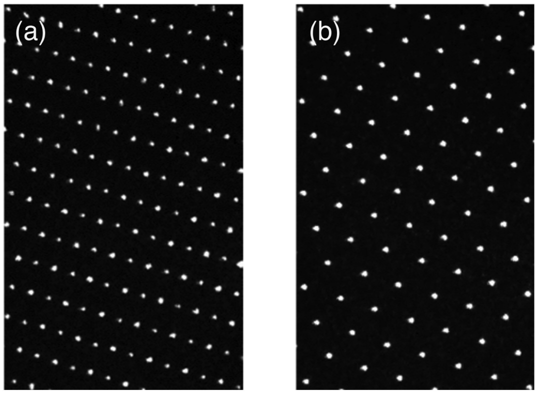

Fig. 5 The projected patterns by VCSEL projector with LC beam multiplier. (a) Two times multiplication dot pattern when LC beam multiplier is with low voltage. (b) Original dot pattern when LC beam multiplier is voltage on. The screen is 70 cm away from LC beam multiplier.

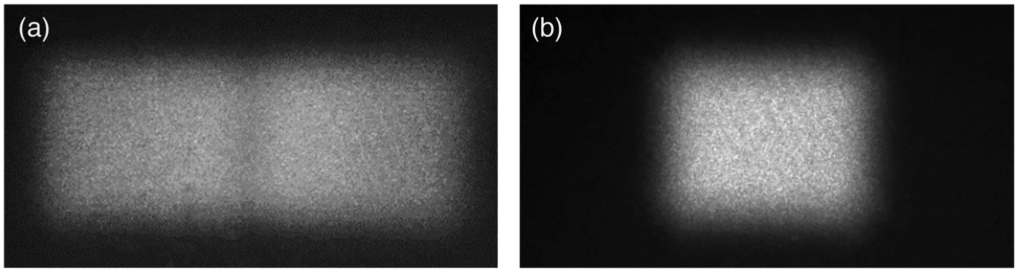

Fig. 6 The projected patterns by switchable pattern illuminator with LC angular extender. (a) 18 deg × 44 deg illumination when LC angular extender was voltage off (b) 18 deg × 22 deg illumination when LC angular extender was voltage on. The screen was 70 cm away from LC angular extender.

was 5 μm in one fixed direction. The projected light patterns on screen 70 cm away were shown in Fig. 6. According to grating diffraction formula, the diffraction angle of 5 μm pitch grating is around 11 deg for 940 nm incident light. Therefore, when voltage was off, the illumination angle extended from 18 deg × 22 deg to 18 deg × 44 deg. When voltage was on, the illumination angle kept 18 deg × 22 deg. The flood contrast for voltage on and off are both <2.

Considering the mobile applications, we developed a driver for LC component. "LQ001" was a 14-pin wafer level chip scale package 1.04 mm × 2.04 mm driver. The LQ001 supported a 6-bit resolution DC to AC converter for setting the driver operating voltage up to $15V_{rms}$ and an 8-bit programmable AC output frequency from 12.8 kHz to 50 Hz. The input supply voltage range was 2.5 to 3.3 V. It could drive the three different types of LC elements in this paper. Besides, it possessed the function of "eye-safety detection." When LC element was broken, the IC driver could detect it and shut VCSEL projector down to avoid unexpected light pattern projecting to human eyes.

5 Conclusion

We integrated a VCSEL projector and LC geometric phase elements to demonstrate switchable pattern projector. We used photo alignment and ODF technology for different geometric phase patterns, such as MLA and gratings to realize LC diffuser, beam multiplier, and angular extender for different application scenarios. Due to the geometric phase property, no extra linear polarizer was needed. These modulation concepts were implemented in the smallest and first ever reflowable LC cell. By our own in-house ink-jet printing system, even 3 × 3 mm LC cell could be realized. The switchable pattern projector could realize two projected patterns by only one

VCSEL projector. The fast-switching time (<5 s), high optical efficiency (>95%), and reflowable properties of LC elements are suitable in mobile application.

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