Geometric Phase-Shift-Based Phase Modulation SLM Using Dual In-Plane Switching Liquid Crystal

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Abstract

In this paper, we propose a dual-panel configuration utilizing commercial in-plane switching (IPS) liquid crystal panels for holographic complex modulation. Phase modulation is achieved through symmetrically-stacked IPS panels, using geometric phase shift to expand modulation range beyond conventional dynamic phase methods. Our demonstration includes a look-up table that maps grayscale inputs to geometric phase shifts. Experimental results verify expansion of phase modulation range using this dual-panel system.

Author Keywords

Holographic display; Phase spatial light modulator; In-plane switching LC; Geometric phase shift

1. Introduction

Holographic displays which are capable of reconstructing holograms can manipulate the wavefront of light. To control light through wave optics, Spatial light modulators (SLMs) that can modulate both the amplitude and phase of light are crucial devices in holographic displays. For amplitude modulation, digital micromirror devices or liquid crystal (LC) SLMs are commonly used. Phase modulation is typically achieved through LC SLMs with different LC modes that utilize the optical path difference of birefringent materials. However, amplitude-only modulation-based hologram reconstruction results in conjugate noise, while phase-only modulation produces no observable image on the SLM surface. Consequently, an ideal holographic display should be a complex SLM which is capable of simultaneously controlling both amplitude and phase. To realize complex SLM, researchers either combine an amplitude SLM (ASLM) and a phase SLM (PSLM) independently [1], or use two PSLMs to achieve complex wavefront control [2].

Most PSLMs utilize the electrically controlled birefringence (ECB) mode of liquid crystals, where LC molecules rotate parallel to the optical axis to create phase modulation through optical path differences. While this configuration enables effective phase modulation without polarization changes, ECB mode LCs are expensive and rarely used in commercial displays. In contrast, commercial displays predominantly use in-plane switching (IPS) mode LCs, where molecules rotate parallel to the panel surface and orthogonal to the optical axis. Although this configuration provides superior viewing angles, it results in limited phase modulation capabilities due to smaller refractive index changes along the optical axis [3].

Implementing phase modulation with IPS mode LC panels presents several challenges. Commercial LC panels, designed primarily for intensity modulation, exhibit limited phase modulation ranges. The amplitude and phase modulation characteristics of the IPS mode LC is calculated with equation (1) using a Jones matrix [3].

$$T = e^{i\frac{2\pi}{\lambda}n_o d}\begin{pmatrix} cos\phi & -sin\phi \\ sin\phi & cos\phi \end{pmatrix}\begin{pmatrix} e^{i\frac{2\pi}{\lambda}(n_e-n_o)d} & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} cos\phi & sin\phi \\ -sin\phi & cos\phi \end{pmatrix} \quad (1)$$

T is the Jones vector of the IPS mode LC, ϕ is the LC tilt angle, n_e is the extraordinary refractive index of the LC, n_o is the ordinary refractive index, d is the thickness of the LC cell, and λ is the wavelength of light. The model can be used to calculate the change in phase and polarization as a function of LC tilt angle.

Geometric phase shift-based phase modulation can be utilized as a method to create larger phase modulation even within the limited phase modulation range of IPS mode. The phase change caused by optical path differences as in equation (1) is called dynamic phase, and ECB mode PSLMs operate based on this principle. In contrast, geometric phase is a phase change induced by changes in polarization states, also known as Pancharatnam–Berry phase.

All polarization states can be mapped to points on the surface of the Poincaré sphere, which allows for the analysis of geometric phase. On the Poincaré sphere, changes in polarization states are represented as a trajectory on the sphere's surface, and when this trajectory forms a closed curve, the geometric phase shift is half of the solid angle created by the path [4]. The polarization state of light can be quantified through Stokes parameters, which can be experimentally determined by measuring the intensity of light passing through specific polarization filters. When using two IPS panels, the polarization state changes once more, which enables the creation of phase modulation greater than twice the dynamic phase change that a single IPS could produce through geometric phase shift.

We propose a system employing two panels to expand the phase modulation range and utilize IPS mode LC panels as geometric phase shift-based phase SLMs. In this configuration, two IPS mode LC panels are symmetrically positioned, with polarization states between the panels changing according to the applied voltage. We removed all polarizers from the panels and designed the system with either the front planes or back planes facing each other. Additionally, to use the system as a PSLM, we created a look-up table (LUT) that determines the geometric phase shift according to the grayscale input to the IPS panels.

2. Proposed method

Figure 1 shows the schematic of the proposed structure and the ideal polarization state changes. IPS mode LCs typically use crossed linear polarizers for intensity control, where voltage-induced LC rotation converts ideally linear to circular polarization. In our system, we remove these polarizers to utilize the IPS panels as active retarders. Figure 1(a) illustrates the system when voltage is applied for grayscale value 0, resulting in no polarization change. Figure 1(c) represents this state on the Poincaré sphere, showing no surface area. Figure 1(b) depicts the system with applied voltage for grayscale value 255, where LC molecular rotation induces polarization changes. In this state, IPS 1 acts as an active retarder, producing -45 degree linear polarization or elliptical polarization, while the symmetrically positioned IPS 2 transforms the light further into circular polarization. Figure 1(d) shows the corresponding polarization changes on the Poincaré sphere, where the created surface area induces a geometric phase shift equal to half of the solid angle.

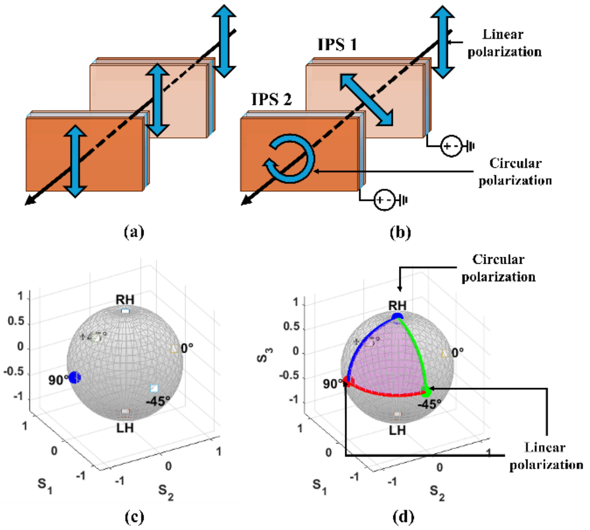


Figure 1. Schematic of the dual IPS mode LC SLM, (a) zero applied voltage. (b) applied voltage. Poincaré sphere analysis of the dual IPS mode LC SLM, (c) zero applied voltage. (d) applied voltage.

Figure 1 represents the ideal polarization changes, and it is difficult to predict what polarization states will appear at grayscale input values between 0 and 255 using only simulations. Therefore, to determine how much geometric phase shift occurs due to the grayscale input data, we can directly measure the polarization states at each IPS to create a LUT for PSLM usage.

To measure polarization states, we obtained the Stokes parameters, known as the Stokes vector, based on the following equation [5]:

$$I \equiv \langle |E_x|^2 \rangle + \langle |E_y|^2 \rangle = I(0°) + I(90°) \tag{2}$$

$$Q \equiv \langle |E_x|^2 \rangle - \langle |E_y|^2 \rangle = I(0°) - I(90°) \tag{3}$$

$$U \equiv Re\langle E_x E_y \rangle = I(45°) + I(135°) \tag{4}$$

$$V \equiv Im\langle E_x E_y \rangle = I(RHC) + I(LHC) \tag{5}$$

I is the total intensity, and Q, U, V represent the three-dimensional vector of Cartesian coordinates that indicate polarization states on the Poincaré sphere. E_x and E_y represent electromagnetic waves in the x and y directions, and I0 is the intensity of linear polarization in the 0-degree direction. Additionally, *I(RHC)* and *I(LHC)* represent the intensities of right-handed circular and left-handed circular polarizations, respectively. Since polarization states can be measured through intensity information, the polarization state at the IPS can be measured if there are filters consisting of 4 linear polarizers and 2 circular polarizers.

However, in the case of SLM using two IPS panels, there is a problem that the polarization does not return to its original state, unlike typical geometric phase-based devices. In this case, since a closed curve is not formed, it is not possible to calculate the solid angle as in conventional geometric phase optics. For noncyclic continuous polarization state changes, the geometric phase can be calculated using the following equation [6]:

$$\Phi_{GP} = arctan\left[\frac{-sin^2\left(\frac{\theta}{2}\right)\sin(\varphi_N)}{cos^2\left(\frac{\theta}{2}\right) + sin^2\left(\frac{\theta}{2}\right)\cos(\varphi_N)}\right] + \frac{\varphi_N}{2}(1 - cos\theta) \tag{6}$$

Φ_{GP} represents the geometric phase, while θ and φ are the polar angle and azimuthal angle in the spherical coordinate system. φ_N denotes the angle at the endpoint of the non-cyclic path, where if the starting point is φ=0, the endpoint is φ=φ_N. Equation (6) calculates the geometric phase for a non-geodesic path whose end points are connected by a geodesic, which represents the shortest path on the Poincaré sphere. This geometric phase is related to the solid angle enclosed by this combined path. Therefore, even in a system where polarization state changes are non-cyclic, we can determine that the geometric phase is half of the solid angle formed by drawing a geodesic between the input polarization state and the final polarization.

3. Experimental results

Figure 2 shows the experimental setup and measurement results. We employed an RV059FBB-N80 BOE 6-inch 2k mono LCD as the IPS mode LC panel, which has a pixel pitch of 50μm and 532nm laser light source. The polarization filters include linear polarizers at 0, 90, 45, and 135 degrees, as well as right-circular and left-circular polarizers, allowing each component to be analyzed.

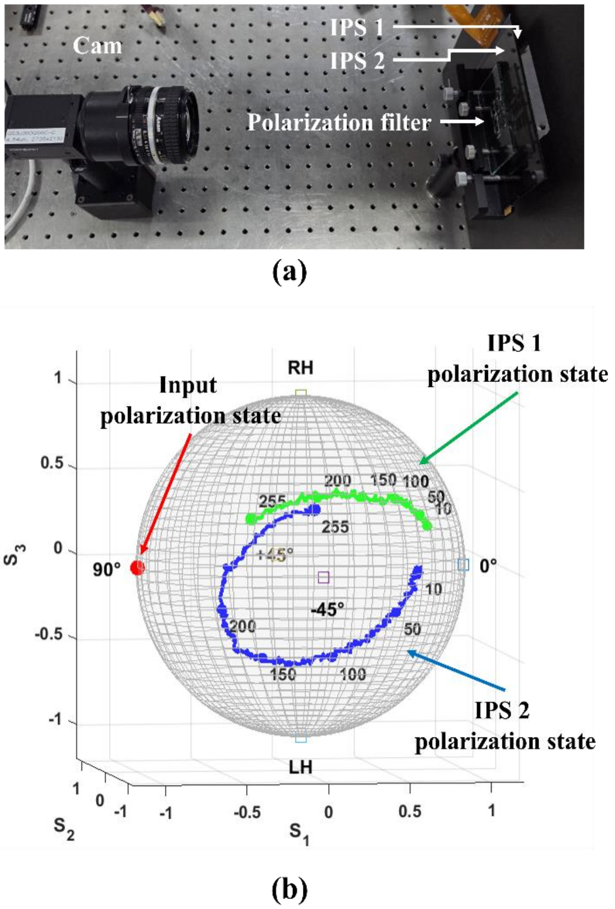
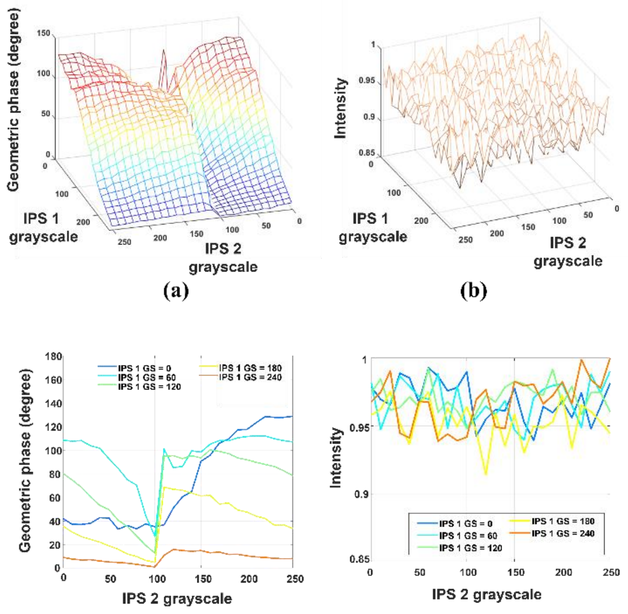


Figure 2. Polarization measurement results of dual IPS system. (a) Experimental setup. (b) Trajectory of polarization states in dual IPS on Poincaré sphere

For the first experiment (represented by the green line), we placed only IPS 1 and measured the polarization states by inputting grayscale values from 0 to 255. For the second experiment (represented by the blue line), we simultaneously set up both IPS 1 and IPS 2 and measured the final polarization states. The laser's polarization was set to 90-degree linear polarization. In this experiment, identical grayscale data was input to both IPS panels. Looking at Fig. 2(b), we can see that there is an inflection point where the final polarization state approaches the initial polarization state as the grayscale reaches 255, indicating that the relationship between grayscale input and geometric phase is nonlinear rather than continuously increasing.



(a) (b)

(c) (d)

Figure 3. Geometric phase and intensity LUT with respect to grayscale in dual IPS system. (a) Geometric phase LUT. (b) Intensity LUT. c) Geometric phase LUT with fixed IPS 1 grayscale. (d) Intensity LUT with fixed IPS 1 grayscale.

Figure 3 shows 3D LUTs of geometric phase and intensity created by measuring polarization data when grayscale inputs to IPS 1 and IPS 2 were independently varied. The intensity data in Fig. 3(b) and (d) shows that while theoretically IPS should not change intensity, variations remain within a 5% range. The geometric phase LUTs in Fig. 3(a) and (c) demonstrate that geometric phase does not increase linearly between 0 and 255, and the polarization state of the first IPS significantly influences the geometric phase. Additionally, we can observe that there are regions where polarization changes dramatically at specific grayscale values (or specific LC stages) of the second IPS.

The maximum geometric phase achievable with this LUT allows for phase modulation of up to 130 degrees, which represents a significant expansion of the phase modulation range compared to the maximum dynamic phase of 35 degrees for a single IPS panel as measured by interferometry.

4. Conclusion

In this work, we proposed a system to expand the phase modulation range of spatial light modulators using commercially available IPS mode LC panels for holographic display. By employing two IPS panels in a symmetric configuration without polarizers, we utilize geometric phase shift effects rather than conventional dynamic phase modulation. The system was demonstrated, and we created a LUT (Look-Up Table) that can be used as a PSLM for holographic displays. We showed that the phase modulation range could be expanded from 35 degrees to 130 degrees.

We aim to find conditions that show more diverse phase and amplitude efficiencies depending on incident polarization angles other than 90 degrees, and will calculate optimized holograms using this LUT.

Acknowledgements

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References

1. Gregory, D. A., Kirsch, J. C., & Tam, E. C. (1992). Full complex modulation using liquid-crystal televisions. Applied Optics, 31(2), 163-165.
2. Goorden, S. A., Bertolotti, J., & Mosk, A. P. (2014). Superpixel-based spatial amplitude and phase modulation using a digital micromirror device. Optics express, 22(15), 17999-18009.
3. Jang, S. W., Choi, W., Kim, S., Lee, J., Na, S., Ham, S., ... & Kim, H. (2022). Complex spatial light modulation capability of a dual layer in-plane switching liquid crystal panel. Scientific reports, 12(1), 8277.
4. Chen, P., Wei, B. Y., Hu, W., & Lu, Y. Q. (2020). Liquid-crystal-mediated geometric phase: from transmissive to broadband reflective planar optics. Advanced Materials, 32(27), 1903665.
5. Berry, H. G., Gabrielse, G., & Livingston, A. E. (1977). Measurement of the Stokes parameters of light. Applied optics, 16(12), 3200-3205.
6. Leinonen, A., Hannonen, A., Partanen, H., Heikkinen, J., Setälä, T., Friberg, A. T., & Hakala, T. K. (2023). Noncyclic continuous Pancharatnam—Berry phase in dual-beam interference. Communications Physics, 6(1), 132.