High Efficiency Electrically-Addressable Phase-Only Spatial Light Modulator

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To realize a high efficiency electrically addressable phase-only modulator, we have coupled a liquid crystal display (LCD) to an optically addressed parallel-aligned nematic liquid crystal spatial light modulator (PAL-SLM) with a set of lenses. Phase modulation exceeding 3π at 532 nm wavelength was obtained. We obtained linear transfer characteristics for phase modulation at various desired phase levels after calibration and adjustment of the transfer characteristics of the PAL-SLM and the LCD. Diffraction efficiency of 40% for binary phase grating and of 90% for 8-level blazed phase grating, which were very close to the simulation values, were observed. The power loss of the readout light was caused when passed through a half mirror, therefore, we examined a setup using an oblique readout light at the modulator. Very high diffraction efficiency was obtained from the setup by optimizing the polarization direction and optical path for this light, and the orientation of liquid crystals. Since the modulator can perform at better than 90% diffraction efficiency and at nearly 100% reflectivity, various high efficiency systems utilizing such modulators are expected.

Key words: spatial light modulator, liquid crystal display, phase-only modulator, diffraction efficiency, oblique incident, phase modulation, amorphous silicon, liquid crystal

1. Introduction

Two-dimensional phase-only light modulators have drawn a great deal of interest in applications for optical correlation systems,1,2 optical interconnection using reconfigurable computer-generated holograms,3 phase contrast technique,4 adaptive optics,5 and so forth. Phase-only modulators are highly desirable for these applications where high transmission efficiency and high discrimination capability are required. Since liquid crystal displays (LCDs) are readily and inexpensively available as commercial components, they have been studied and utilized as phase modulators. However, most LCDs at present cannot achieve a real 2π phase modulation required for the above mentioned applications and have unavoidable drawbacks such as energy loss caused by a limited aperture size. To realize a practical phase modulator, a nonpixelized, optically addressed, parallel-aligned nematic liquid crystal spatial light modulator (PAL-SLM) has been developed. A large depth of phase-only modulation based on the electro-optical characteristics of a parallel-aligned nematic liquid crystal layer has been obtained.6 In many applications, a phase-only spatial light modulator must be controllable and programmable by a computer, and must provide real-time display of computer-generated patterns such as computer generated hologram (CGH). We therefore developed a computer controllable and programmable two-dimensional phase modulator system by combining a PAL-SLM and an LCD with a lens system. The diffraction efficiency characteristics for binary phase grating were measured.7 The results were very close to the theoretical values and in good agreement with computer simulations. Such a phase modulation system which is programmable for various phase levels is required for many practical applications.

We describe here the phase modulation characteristics and diffraction efficiency characteristics for blazed phase grating of the LCD-coupled PAL-SLM demonstrating the programmable capability of the modulator system for various phase levels. The diffraction efficiency characteristics for an oblique readout light are also presented. This light enables one to avoid power loss of a readout light due to a half mirror.

2. Parallel-Aligned Nematic Liquid Crystal Spatial Light Modulator (PAL-SLM)

Figure 1 shows a structure of the PAL-SLM. An amorphous silicon (a-Si:H) photo-conductive layer is used as the optical addressing material, and a parallel-aligned nematic liquid crystal layer as the light modulating material. A dielectric mirror is sandwiched between the liquid crystal and the a-Si:H layers in order to enhance the reflective performance of the device. In ordinary twisted nematic modulators, the liquid crystal molecules are aligned in spirals as shown in Fig. 2(a), when no electric field is applied. With an electric field applied across the layer, the liquid crystal molecules become tilted and cause a modulation both in polarization states, and consequently in the phase of the polarized read-out light. In this case, the phase-only modulation cannot be achieved. In the PAL-SLM, the liquid crystal molecules are aligned...
in parallel, not in spirals, as shown in Fig. 2(b), when no electric field is applied. With an applied electric field, the molecules are tilted to the substrates. When the polarization direction of the read-out light is parallel to the axis of the liquid crystal molecules, only the reflective index along the optic axis is changed, therefore, phase-only modulation can be achieved. The characteristics of the PAL-SLM are summarized in Table 1.

Table 1. Characteristics of the PAL-SLM.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>(&lt;30) ms (\text{(rise)}) ((\text{max. } 1) ms)</td>
</tr>
<tr>
<td>Resolution</td>
<td>(&gt;50) lp/mm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>(20) (\mu)W/cm(^2)</td>
</tr>
<tr>
<td>(\pi) modulation</td>
<td>(\lambda=552) nm</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>(99.9%)</td>
</tr>
<tr>
<td>Phase modulation</td>
<td>(&gt;2\pi) radian</td>
</tr>
<tr>
<td>Active area</td>
<td>(20) mm (\times) (20) mm</td>
</tr>
</tbody>
</table>

Table 2. Specifications of the coupling lenses.

<table>
<thead>
<tr>
<th>Type</th>
<th>Telecentric system of both sides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical aperture</td>
<td>0.013</td>
</tr>
<tr>
<td>Magnification</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of lenses</td>
<td>8</td>
</tr>
</tbody>
</table>

Fig. 3. Photograph of the LCD-coupled PAL-SLM module.

3. LCD-Coupled PAL-SLM

A photograph of the LCD-coupled PAL-SLM module is shown in Fig. 3. The LCD (SONY LCX012BL) has an array of \(640 \times 480\) pixels and the maximum contrast ratio of 250:1. The diagonal size is 1.3 inches. The pixel pitch for both horizontal and vertical axes is 41.4 \(\mu\)m. The LCD and the PAL-SLM are coupled by a set of lenses for 1:1 imaging. This lens assembly was specially designed to transmit an addressing image efficiently from the LCD to the PAL-SLM and at the same time to eliminate the artifact and diffraction noise due to the pixel structure of the LCD. The specifications of the coupling lenses are shown in Table 2. Optical transfer function (OTF) of the coupling lenses, when the collimated light of a laser diode \(\lambda=680\) nm enters the lenses parallel to their optical axis, is shown in Fig. 4. The spatial frequency of the pixel structure of the LCD is 24 lp/mm, therefore the structure does not transfer through the lenses. The spatial frequencies of the patterns generated on the LCD are below 12 lp/mm, so that signals are transferred efficiently.
4. Experiment

The experimental setup for studies of phase modulation characteristics of the LCD-coupled PAL-SLM is shown in Fig. 5. We employed a laser diode (LD, Toshiba TOLD9150, 30 mW) with wavelength of 680 nm as write-in light for the PAL-SLM. A second harmonic generation (SHG) of YAG laser with wavelength of 532 nm (Uniphase, 4601-010-1000, 10 mW) was collimated by a lens (f=300 mm), and the collimated light was employed as a readout light. The intensity of the readout light was 1 mW/cm². In the intensity modulation mode, the direction of LC molecule was adjusted to 45 deg corresponding to the polarization direction of the readout light. In the phase-only modulation mode, the analyzer was removed and the direction of the LC molecule was adjusted parallel to the polarization direction of the readout light. The PAL-SLM was driven with ±2.5 V square wave voltage at 1 kHz throughout all the measurements mentioned in this paper.

4.1 Transfer Characteristics

To obtain as many programmable phase levels as possible, we have made a transfer characteristics of the LCD-coupled PAL-SLM linear by calibrating and adjusting transfer characteristics of the LCD and the PAL-SLM. Transfer characteristics of the PAL-SLM, the LCD, and the LCD-coupled PAL-SLM were measured, respectively.

Transfer characteristics of the PAL-SLM are shown in Fig. 6(a). The horizontal axis shows write-in intensity of the PAL-SLM. The vertical axis shows amount of phase modulation of the PAL-SLM. We measured the modulated readout light intensities at various write-in intensities in the intensity modulation mode of the PAL-SLM. The measured readout intensity (I) is related to the phase modulation (φ) as...
\[ I = (I_{\text{max}} - I_{\text{min}}) \sin^2 \left( \frac{\phi}{2} \right) + I_{\text{min}} \]  

where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and the minimum measured intensities, respectively, phase modulation is thus obtained. Transmission of the LCD is shown in Fig. 6(b). The horizontal axis shows input signal levels of VGA generated in a computer. Uniform patterns with different gray levels according to the signal levels were displayed on the LCD and the transmission for each level was measured. Transfer characteristics of the LCD-coupled PAL-SLM are shown in Fig. 6(c). The horizontal axis shows input signal level to the LCD and the vertical axis shows phase modulation amount of the PAL-SLM. Collimated light of the laser diode is used for illuminating LCD and the intensity was 1 mW/cm² in front of the LCD.

The transfer characteristics of the PAL-SLM and the LCD are not linear, however, the resulting transfer characteristics of the LCD-coupled PAL-SLM have been linearized. Using these linear transfer characteristics, it is obvious that a phase pattern with various desired phase levels can be designed and achieved easily. At wavelength of 532 nm, phase modulation of more than 3\( \pi \) can be achieved. The overall results show that the LCD-coupled PAL-SLM has adequate phase modulation characteristics exceeding 2\( \pi \) modulation for most applications involving two-dimensional phase modulation.

### 4.2 Diffraction Efficiency Characteristics for Multi-Level Phase Grating

Higher diffraction efficiency can be obtained by using the multi-level phase grating. Therefore, the diffraction efficiency characteristics of multi-level phase grating for the LCD-coupled PAL-SLM system was measured. Multi-level intensity gratings displayed on the LCD were optically addressed to the PAL-SLM so that the multi-level phase gratings were formed in the PAL-SLM. To get the highest diffraction values, we calibrated the input signal levels to the LCD according to the transfer characteristics of the LCD-coupled PAL-SLM. Four and eight steps over a phase modulation range from zero to 2\( \pi \) radians of blazed grating as well as binary grating were examined. Pictures of diffraction patterns for no modulation, binary grating, 4-level blazed grating, and 8-level blazed grating are shown in Fig. 7(a), (b), (c), and (d), respectively. The spatial frequency of each grating was 3.1 lp/mm (8 pixels width). The experimental results of the 1st order diffraction efficiency as well as simulation values for binary grating, 4-level blazed grating, and 8-level blazed grating are shown in Table 3. Here, the 1st order diffraction efficiency, \( \eta_1 \), is defined as,

\[ \eta_1 = \frac{I_1}{I_0} \]  

where \( I_1 \) is the intensity of the 1st order diffraction pattern, and \( I_0 \) is the 0th order light intensity of the diffraction without modulation. The zero order intensity is equal to the total light intensity of all the diffraction when the modulation occurs. As shown in Fig. 7 and Table 3, the diffraction efficiency increases as the number of steps increases.

<table>
<thead>
<tr>
<th>Number of levels</th>
<th>Phase grating</th>
<th>1st order diffraction efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulation</td>
</tr>
<tr>
<td>2</td>
<td>2( \pi )</td>
<td>40.5</td>
</tr>
<tr>
<td>4</td>
<td>2( \pi )</td>
<td>81.1</td>
</tr>
<tr>
<td>8</td>
<td>2( \pi )</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Fig. 7. Pictures of diffraction patterns, (a) no modulation, (b) binary grating, (c) 4-level blazed grating, (d) 8-level blazed grating. The spatial frequency of each grating was 3.1 lp/mm.
of the blazed phase grating rises and the diffraction efficiencies for the three gratings were very close to the simulation values.

4.3 Diffraction Efficiency Characteristics for Oblique Incident Readout Light

In the setup shown in Fig. 5, a half mirror is used to separate incident light and reflected light of the PAL-SLM. When the light goes through a half mirror, the readout light intensity becomes half. In the setup shown in Fig. 5, the readout light of the PAL-SLM goes through the half mirror twice, therefore, the intensity is reduced to one-fourth the original intensity. To avoid loss of the readout light due to the half mirror, we examined the oblique incident setup shown in Fig. 8.

To maintain a direction of polarization for the readout light and obtain high diffraction efficiency, we set the polarizing direction of the readout light, optical path for the readout light, and the orientations of liquid crystal molecules in the PAL-SLM in the way shown in Fig. 9. The polarization and an optical path for the readout light lie in the same plane, the YZ plane, as shown. The liquid crystals also tilt in that plane during operation. With this setup, the state of polarization for the incident light and the reflected light are identical.

Diffraction efficiency characteristics for binary phase grating of the LCD-coupled PAL-SLM were measured using the setup in Fig. 8. Binary intensity grating of vertical lines was addressed to the LCD and monitored. The duty ratio of the grating was 50%. Figure 10 indicates the diffraction efficiencies for the 1st order diffraction lights with various oblique incident angles when the phase modulation depth of the PAL-SLM was at $\pi$ radians and the spatial frequencies of the gratings were varied. The incident angles of 0 deg, 15 deg, and 30 deg were examined. When diffraction efficiency of the incident angle of 0 deg was measured, the setup shown in Fig. 5 was used. The high diffraction efficiencies were achieved even when the oblique incident readout light was used. Reflectivities of the anti-reflection (AR), the ITO, and the dielectric mirror placed in the PAL-SLM were also examined. The reflections of the AR and the ITO should be removed because the reflected light is not modulated in the SLM and becomes noisy. The reflectivity of the dielectric mirror should be high because if the reflectivity increase, power loss in the SLM decreases. The measured reflectivities of the AR, the ITO, and the dielectric mirror were less than 0.1%, less than 0.1%, and more than 99%, respectively, over a range from 0 to 30 deg of incident angle. If the incident angle is decided and the AR, the ITO, and the dielectric mirror are designed for the incident angle, these performances are even improved.

Thus, the performances such as the phase characteristics do not depend on the small oblique incident angle. We confirmed that setups such as those shown in Figs. 8 and 9 would be feasible and effective in practical applications.

5. Conclusions

We have developed a phase modulation spatial light modulator system directly controllable by a computer. At a wavelength of 532 nm, the linearized transfer characteristics of more than $3\pi$ phase modulation was ob-
tained after calibration and adjustment of the transfer characteristics of the PAL-SLM and the LCD. The diffraction efficiency of 90% for 8-level blazed phase grating, which is very close to the theoretical limit, was also observed. Diffraction efficiency characteristics for oblique incident readout light were examined to study the diffraction characteristics without using a half mirror. With proper arrangement among the polarization direction and optical path for the readout light, and the liquid crystal orientation, we obtained very high diffraction efficiency for various oblique incident readout lights. This phase modulator can perform at diffraction efficiency of better than 90% for multilevel blazed grating, and at nearly 100% reflectivity. We confirmed that this modulator has sufficient phase modulation capability for practical applications such as optical interconnection, optical correlator, and adaptive optics.

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