Micro-displays for Holography

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Abstract. The characteristics of modern micro-displays are considered and compared. These devices in principle are capable not only to display the computer generated information blocks on the projection screen but also to send them into the holograms, and even to form these blocks as the digital holograms reconstructed from a micro-display screen.

Introduction

In principle, modern micro-displays are capable not only to display the computer generated information blocks on the projection screen but also, as the electrically controlled spatial light modulators (SLM), to send the formed information into the photosensitive medium for recording the holograms. One can expect also, that properties of SLMs will allow real time forming the information blocks as the digital holograms that can be reconstructed directly from a micro-display screen [1, 2].

The following types of micro-displays can be used for spatial light modulation [2-7]:

- AM LCD - light transmitting liquid crystal displays with Nematic Liquid-Crystal (NLC) as the electro-optical display medium, and Active-Matrix addressing scheme based on thin-film-transistor drivers on the glass surface;
- LCoS and FLCOS - reflective Liquid Crystal (on Silicon) displays with active matrix addressing scheme embedded into a silicon substrate, accordingly with LC of nematic type and Ferroelectric LC of smectic type (FLC) as the electro-optical display medium;
- DMD displays - reflective micro-electromechanical (on the work principle) Digital Micro-mirror Devices with a matrix of deflected micro-mirrors and active-matrix addressing scheme embedded into a silicon substrate.

Next, we will consider in more details the features of used SLM technology and parameters achieved in SLM, to compare their abilities (present and future) for holography.

Characteristics of SLM

Light-Transmitting LC SLM [5, 6]

All light-transmitting SLMs are liquid crystal devices using NLC. They are addressed by means of the so-called "active matrix" of electronic keys (drivers) based on thin-film transistors, usually located in a corner of each pixel.

The most well-known and commercially available SLMs of such a type are SLMs of companies HOLOEYE and MEADOWLARK OPTICS producing different variants of light-transmitting devices for the modulation of phase, amplitude and polarization of light. For example, HOLOEYE SLM “LC-2112” with the format of 1024x768 pixels and with a pitch of 36 microns is capable to form data blocks of 256 gray levels (8 bits) with the speed of 60 Hz providing a pure phase shift up to $2\pi$ at the wavelength of 450 nm and up to $1\pi$ at the wavelength of 800 nm with a contrast ratio up to 1000:1. Phase SLM “HEX” of the company MEADOWLARK OPTICS has the disc-shaped working aperture and 127 pixels of the hexagonal form, and this SLM as a phase-only mask can correct linearly polarized wave front after its passing through the aberrational medium.
Reflective SLMs Based on LCoS Structure [2, 3, 5-8]

Pixels in the reflective micro-display are addressed by means of electronic keys formed in the silicon wafer using CMOS technology. At the top level of metallization on the silicon, they create the matrix system of aluminum mirrors acting as control electrodes for each individual LC electro-optical cells and at the same time reflecting the light incident to this cell. Visualization of information formed in the micro-display is implemented due to LED or Laser Diode sources, when the light is reflected from aluminum mirrors and passes twice through LC layer.

Recent advances in integrated circuit technology and LCD materials allowed to Japanese companies JVC and NHK [8] to create LCoS based micro-display with the format 8Kx4K, pixel pitch of 4.8 µm and to increase the optical contrast ratio up to 100K:1. The typical light transmittance is of 70-80%, optical response time is of about 1 ms, and temperature interval is from -50 to +100 °C for micro-display storage and from -21 to +80 °C for its operation. Light reflecting regime and effective heat dissipation through a silicon allowed reaching the density of the luminous flux of 2100 lm / cm².

The most well-known and commercially available monochrome SLMs are devices of mentioned companies HOLOEYE and MEADOWLARK OPTICS offering a large range of products to choose. In a series of SLM HOLOEYE [5] the micro-display “GAEA” for phase-only light modulation surprises with the format 4094x2464 (about 10 megapixels), resolution (133.5 lines / mm and pixel pitch of 3.74 µm), diagonal size of the working matrix of 0.7 inches, and 256 gray levels (8 bits). However, it operates with the rate of 24 frames per second, while the micro-display with the format of 3840x2160 pixels changes images with the rate of 30 fr. / sec. The frequency of 60 Hz is reached in phase-only SLM “PLUTO” and “LETO”, which have the format of 1920x1080 pixels (HD) with the pixel pitch of 8.0 µm and 6.4 µm respectively, and a screen diagonal size of 0.7 and 0.55 inches. SLM “LC-R-721” for amplitude-phase modulation is characterized by increased rate (the frequency is of 180 Hz), which a twisted nematic LC structure provides.

MEADOWLARK OPTICS [6] suggested for the phase, amplitude and mixt modulation of light the one-dimensional array of 12,288 elements (a pitch is of 1.6 µm, and a gap between pixels is of 0.6 µm) manufactured on LCoS technology and now well demanded in holography. The diffraction efficiency of such a grating reaches 95%, and the resolution is 500 levels in the interval of phase changing up to 2 π. In addition, for the same purposes the company produces the matrix SLMs with the formats of 256x256 and 512x512 pixels.

Color images are usually formed in the optical system with three LCoS micro-displays in optical RGB- channels. However, using NLC with increased speed of switching and Field Sequential Color (FSC) method to form color images using three alternately operating bright RGB LEDs (or laser diodes) the company Syndiant (USA) has developed the technology “VueG8” of creating the micro-display for pico-projectors, which is suitable for digital holography also [7]. FSC- method is illustrated in Fig. 1 in the comparison with the so far most common space method of forming colors using subpixels. FSC- method does not require sub-pixels and color RGB- filters, and therefore provides less structured (smoothed) and twice brighter images, as well as provides technological advantages, since at the same display format now three times less number of addressable pixels is required. Furthermore, FSC used LCoS structure has a simpler design and includes not optical (more complex) but electric elements of testing its operation ability.

![Figure 1. Comparison of the spatial (left) and FSC (right) methods of forming the pixel colors.](image-url)
Micro-Displays and SLMs Based on the Structure FLCoS [9-12]

Micro-displays with ferroelectric LC are different from NLC-LCoS since FLC can be switched tens times faster than NLC, and short bipolar voltage pulses are used for this. This resulted in increased requirements to the technology. However, CMOS technology, using large amounts of interconnects in a compact package allowed obtaining the small size of pixels, low power consumption and high-speed change of images generated in FLC (up to several thousand frames per second). The technological task of creating the electro-optical cell with FLC layer thickness of about 1 µm (to be achromatic) was also solved.

In FLCoS based micro-displays first developed in the company DisplayTech the FLC materials with bistable modulation characteristic are used. Therefore, to form in devices the gray scale (halftones) and colors they modulate additionally electronic signals, exchanging by means of this the high modulation frequency (a few kHz) to corresponding number of halftone gradations in bits. As a result, the refresh rate decreases down to 240-360 Hz but FSC method can be used with a success due to three RGB light emitting diodes or a rotating disk with three RGB filters.

The University of Cambridge is designing the micro-display, in which the new FLC materials with continuous gray scale are tested. Such FLCs developed in the P.N. Lebedev Physical Institute (Russia) allow forming color images, including by FSC method, with very high rate, up to 4 kHz (Fig. 2) and more [13]. Supposed characteristics of FLCoS with such FLC are indicated (*) in the Table 1 (below).

![Figure 2. The modulation characteristic of FLC cell with 1.7 µm thickness (the composition HF-32C) at the frequency of 4 kHz while reducing (1) and increasing (2) of the control voltage amplitude.]

The companies Kopin and Micron Technologies produce several variants of FLCoS based micro-displays of VGA, WVGA, SVGA and XGA formats with a diagonal of working area from 0.4 to 0.5 inches [10]. They consume less than 100 mW of power and form images with illumination of up to 100 lumens. The company Forthdd designed micro-displays of even larger format [11]: WXGA = 1280 x 768 (with a pixel pitch of 13.62 µm), SXGA = 1280 x 1024 (with a pixel pitch of 13.62 µm) and QXGA = 2148 x 1536 (with a pixel pitch of 8.2 µm). Moreover they can operate in the temperature interval from -10 to + 65 °C (storage temperature is from -40 to + 80 °C). All of them can be used as SLMs for amplitude-phase modulation of monochromatic light. Furthermore, high-speed (up to 4.5 kHz) SLMs “QXGA-3DM” were applied as binary (0 or π) phase modulators of the coherent light, providing the diffraction efficiency of 10% in the first order at the wavelength of 544 nm [12].

DMD Micro-Displays [14-17]

DMD - micro-displays, manufactured by the so-called DLP («Digital Light Processing») technology, developed in Texas Instruments Inc., are among the fastest and brightest. Here images are formed by a matrix of electrically controlled micro-mirrors located on a silicon substrate, in which, like in LCoS, the control electronics is built-in. At applying an electrical signal to electrodes of a micro-mirror
cell the thin and lightweight mirror mounted on a hinge, due to the electrostatic force deviates for exactly one angle (such as 20°). The gap between the mirrors is only about 1 µm. The light beam reflected from the mirrors falls or does not fall into the output window, so the optical contrast reaches 10,000:1. Grayscale and colors of images are arranged due to repeating the micro-mirror deflections with different frequency. The speed of optical switching defined by the time of mirror deflection, is high enough for creating the color images on FSC-method.

Currently, many electronic companies use DLP technology for the manufacture of video projectors of the general-purpose: miniature helmet-mounted and near-eye displays, SLMs, smart phones, pico-projectors, and auditorium and theatre video projectors [18]. The format of projectors varies from VGA (640x480) to HDTV (1920x1080) and WQXGA (2560x1600), and light power varies from 20-50 lm to 4000 lm.

Texas Instruments Inc. continues to produce and improve the key element of these devices - DMD matrix [17]. One of the latest achievements is the chip “DLP4500”, which has a resolution of 1280 x 768 pixels, pitch of 7.6 µm, frame rate of 120 Hz for 8-bit data, and 4225 Hz for binary data; it is addressed with the speed of 4.4 Gb / sec and consumes 407 mW. The other newest chip “DLP4710” has a resolution of 1920x1080, pitch of 5.4 µm, diagonal size of about 12 mm, and the micro-mirrors deflect the light by ±17°. Except this chip the display system includes the controller “DLPC3439” and drivers DLPA3000 / DLPA3005 PMIC / LED. Parameters of latest developments of DMD-matrices demonstrate that DLP-devices are able to overcome the problem of reducing the pixel size (a matrix pitch of 17 microns was for many years). Accordingly, the rate of mirrors deflection and frame rate increased: for binary images the rate is already close to 8 kHz.

Comparison of Micro-Displays

It is convenient to compare micro-displays using the table, which qualitatively by dint of sings "plus" (like in [3]) illustrates display characteristics of micro-displays considered above.

Table 1. Comparative characteristics of the micro-displays (preferably where more signs "plus".

<table>
<thead>
<tr>
<th>Type of a micro-display Characteristics</th>
<th>AMLCD (color filters)</th>
<th>LCoS (color filters)</th>
<th>LCoS (FSC)</th>
<th>FLCoS (binary response)</th>
<th>FLCoS (gray scale)*</th>
<th>DMD (FSC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of optical switching</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Brightness</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Light polarization</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Complexity of electronics</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Complexity of optics</td>
<td>++++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Format (resolution)</td>
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<td>HD</td>
<td>HD</td>
<td>HD</td>
<td>SVGA</td>
<td>HD</td>
</tr>
<tr>
<td>Control regime (analog, digital)</td>
<td>A, A, D</td>
<td>A, D</td>
<td>A, D</td>
<td>A, D</td>
<td>D</td>
<td>D</td>
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<tr>
<td>Temperature requirements</td>
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<td>++</td>
<td>++</td>
<td>+</td>
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<td>+++</td>
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<td>Life time</td>
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<td>++++</td>
<td>++++</td>
<td>++++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Maturity of the technology</td>
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<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

Summary

The characteristics of modern micro-displays are considered and compared.

Micro-displays based on LCoS structures have a wide range of NLC operating modes and can spatially modulate the light as a dynamic optical element. Micro-displays based on the structure FLCoS added the ability to work without color filters and with an order of magnitude faster speed, but do not allow until now to carry out the phase-only modulation of the light beam. For most of characteristics the best positions belong to DLP technology, but it is also the most difficult and
expensive. None of the micro-displays provides at present the resolution and switching speed to form the digital holograms in real time (it is necessary not less than $10^{11}$ pixels/sec according to [1]).

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References


