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Microdisplays in spatial light modulators

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Abstract. **The characteristics of modern microdisplays based on liquid crystals and electromechanical micromirrors are considered. These displays, being spatial light modulators, can rapidly generate large optical data arrays to be recorded as holograms and used for data processing. The potential of microdisplays for visualising digital holograms in real time is estimated.**

Keywords: *microdisplays, spatial light modulators, data processing, holography.*

1. Introduction

The holographic method makes it possible to observe three-dimensional images reconstructed from a hologram without stereo glasses and with a continuous parallax, i.e., with maximum similarity. At the same time, using focused laser beams, one can record an image (a data page) in a hologram with a very high density (~10^4 bit mm^{-2}). A number of the so-called multiplexed holograms can be recorded and independently reconstructed in the same portion of a recording medium without any significant degradation of quality. Moreover, shifting a beam in a volume recording medium, one can record data at different depths, due to which an optical holographic archival memory can be implemented [1].

Since a hologram is a superposition of two optical fields, it can be modelled mathematically, calculated by a computer, and presented digitally on a recording medium, from which the initial three-dimensional image can be reconstructed by a laser beam. This hologram property is widely used in practice to design flat and lightweight holographic optical elements (lenses, mirrors, diffraction gratings, etc.), convenient for use in optical schemes, and generate complex holographic filters, invariant to geometric transformations of recognised images; it is also applied in interferometry to analyse, synthesise, and compare wave fields (e.g., when solving practical problems of nondestructive monitoring of details in industry). Based on the principle of reconstruction of computer-synthesised holograms, one can also design a real-time interactive holographic display.

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Data arrays are formed using electrically controlled spatial light modulators (SLMs), which can modulate the amplitude, phase, or polarisation of light waves in space and transfer the formed image on an optical (laser) carrier to optical data storage, processing, and displaying systems [1–3].

In practice, displays (i.e., displaying devices providing optical pickup – reading of imaged data by a laser beam) are used as SLMs. The high-speed operation of displays is due to their compactness and control by means of micro- and integrated circuits; for this reason, they are referred to as microdisplays. Despite the small screen size (generally, from centimetre to inch in diagonal), these are full-fledged displays with a standard control, conventional operating speed (60–90–120 frames s^{-1}), and a number of screen elements (a format) on the order of 1000 × 1000 pixels or more. Being used jointly with projection optics elements, they can display images of several or even several tens of square metres on a projection screen.

The following types of microdisplays are the most widespread and commercially important for spatial light modulation [3–8]:

(i) active-matrix liquid crystal displays (AMLCDs): light-transmissive liquid crystal (LC) displays with an active control matrix based on thin-film transistors and nematic LC (NLC) playing the role of the electro-optical medium of the screen;

(ii) liquid crystal on-Si (LCoS) and ferroelectric LC on-Si (FLCoS): light-reflecting LC displays with an active control matrix built-in into a silicon substrate and a nematic LC or smectic ferroelectric LC (FLC), acting as the electro-optical medium of the screen; and

(iii) digital micromirror device (DMD) displays: light-reflecting microelectromechanical digital displays with an active control matrix, built-in into a silicon substrate, and a matrix of deflected micromirrors mounted on this substrate.

Any of the aforementioned microdisplays should be supplemented with a unit for reading the data displayed, including a light source and an optical scheme with necessary elements (lens, filters, polarisers, despeckler, etc.); the optical quality of the microdisplay and reading unit should be sufficiently high to provide a distortion-free transfer (projection) of data from the microdisplay screen according to their purpose: to be recorded in a hologram, transformed, displayed, etc.

In this review, we omit a number of popular microdisplays that cannot be applied as SLMs: LBS microdisplays with laser beam scanning by means of one or two microelectromechanical mirrors (used in picoprojectors), organic light-emitting diode (OLED) microdisplays based on a thin layer of organic electroluminescent material (used in screens of mobile telephones and gadgets), and light-emitting microdisplays based on LED arrays (used in bright advertising panels and indicators).

Below we consider in more detail the specific technological features of the SLMs used in practice, their record parameters, and their fields of applications (current and promising) in holography and data processing.

2. SLM characteristics

2.1. Light-transmissive LC SLMs [6, 7]

All light-transmissive SLMs are based on NLCs. A schematic diagram of the electro-optical modulating part (screen) of this SLM (display or microdisplay), which is an LC cell, is shown in Fig. 1b. It consists of two plane-parallel insulating plates (*3*) (mostly glass substrates), the distance between which is generally 1.5–10 μm. This distance is fixed using special calibrated gaskets or balls (spacers). Transparent conducting coatings (*4*) are deposited on the inner plate surfaces to provide an electric effect in the LC. The gap between the plates is filled with LC material (*7*), whose optical anisotropy may change with a change in the amplitude and width of voltage pulses applied from generator (*1*) to conducting coating (*4*). Protective insulating film (*5*) and polymer film (*6*), which provide the initial uniform orientation of the long axes (director) of LC molecules in the absence of electric field, were deposited on the coatings. Thin-film polaroids (*2*) can be glued on the external side of glass plates to transform the phase-polarisation light modulation into the amplitude modulation.

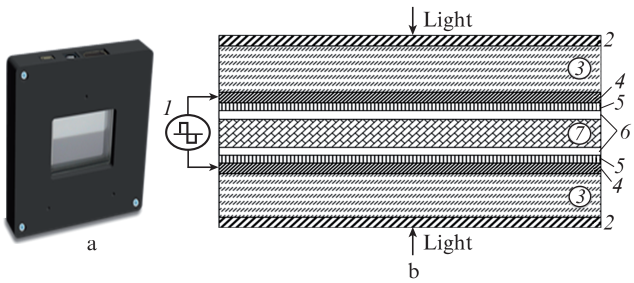


Figure 1. (a) Appearance of the light-transmissive SLM LC-2012 (Holoeye) and (b) a schematic diagram of the electro-optical LC cell: (*1*) control voltage generator; (*2*) thin-film polaroids; (*3*) glass substrates; (*4*) transparent conducting coating (ITO); (*5*) transparent insulating film; (*6*) transparent anisotropic (orienting) film; (*7*) LC layer.

Light-transmissive SLMs are addressed using the so-called active arrays of electronic switches based of thin-film transistors, which are generally located in the corner of each pixel. For this reason, and in view of the presence of contact buses in the interelectrode gaps, the filling factor of SLM screens is insufficiently high (~60%).

The most popular and commercially available SLMs are those produced by Holoeye and Meadowlark Optics, who manufacture light-transmitting devices of different types for modulating the phase, amplitude, and polarisation of light. For example, the LC-2012 SLM (Holoeye) (Fig. 1a), containing 1024 × 768 pixels with a period of 36 μm, can form data blocks with 256 grey levels (8 bits) at a rate of 60 frames s^{-1}, providing a phase only shift up to 2π at a wavelength of 450 nm and 1π at a wavelength of 800 nm, with a contrast ratio as high as 1000:1. The phase SLM of the HEX type (Meadowlark Optics) has a working aperture shaped as a disk and 127 hexagonal pixels; it may perform correction (as a phase only mask) of a linearly polarised wavefront transmitted through an aberration medium.

2.2. LC SLM based on the LCoS structure [3, 4, 6–11]

A schematic diagram of an individual element of a light-reflecting NLCoS structure, its position in the microdisplay matrix, and external appearance (with the framing and contact buses for connection with a separately located controller) are shown in Fig. 2.

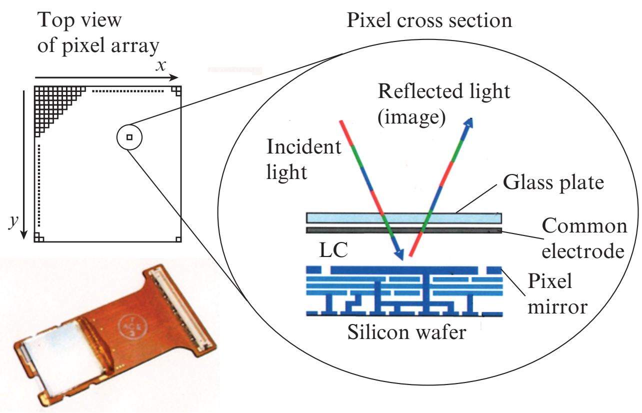


Figure 2. Schematic of an LCoS microdisplay element (on the right), its position in the array, and the top view of the microdisplay with a screen and contact bus (on the left) (ForthDD [12]).

The microdisplay elements are addressed using the electronic switches formed in a silicon wafer by the CMOS technology. A matrix of aluminium mirrors is fabricated in the upper metallisation layer on silicon; these mirrors act as control electrodes for each individual electro-optical LC cell and at the same time reflect the light incident on the cell. To provide an electrical insulation between the electrodes, small gaps filled with a light-blocking material are formed in the mirror matrix. Spacers are made in some gap intersections, which specify the LC cell thickness (several micrometres) and support the glass plate with a common transparent electrode, insulating protective layer, and a polymer layer for LC orientation. The liquid crystal is filled into the gap between the silicon and glass plates, and the entire cell is sealed. The structure is connected (via a bus) with the controller, which forms the initial set of electronic data to be displayed.

The data generated in the microdisplay are visualised using LED illumination, reflection of light from the mirrors and double transmission through the LC layer. A projection optics is used to transfer the image formed in the LC layer to the output channel (hologram, fibre, projection screen, etc.).

This technology is characterised by simplicity (the use of standard microelectronic processes), very small pixel size (3–5 μm), high filling factor (about 93% at a pixel period of 4 μm and a gap of 0.2 μm between pixels), and low fabrication cost [3]. Based on the latest achievements in the integrated circuit technology and LC materials, JVC and NHK companies (Japan) [9] have developed an LCoS microdisplay with

8K × 4K pixels and a period of 4.8 μm and increased the contrast ratio to 100K : 1. The typical light transmittance of this microdisplay is 70%–80%, the optical response time is ~1 ms, the storage temperature is varied from –50 to 100 °C, and the working temperature range of the LC phase is from –20 to 80 °C. The use of the reflection geometry and the efficient heat sink through the silicon plate made it possible to attain a light flux density as high as 2100 lm cm^{-2}.

Another Japan company (Hamamatsu) proposes a number of different SLMs of LCoS type for phase modulation of light [10, 11]. Three series (X10468 and X13267 of the SVGA format (800 × 600 pixels) and X13138 of the SXGA format (1280 × 1024 pixels)), with devices of nine types in each series, characterised by a light reading spectral range of several hundreds of nanometers (for example, 400–700 nm) or only 50 nm, overlap a spectral range of 400–1550 nm. The phase change from 0 to 2.25π is linearly related to the change in the input signal (256 levels are fixed). The reading efficiency is ~80% for broadband SLMs and reaches 98% for narrowband SLMs (equipped with a dielectric mirror). However, a rate of 60 frames s^{-1} is provided for only about a half of devices. The typical matrix size in the aforementioned series is 15.8 × 12 mm, 9.9 × 7.5 mm, and 15.9 × 12.8 mm, respectively. All SLMs are controlled by a personal computer using a standard digital interface.

Other well-known and commercially available devices are monochromatic SLMs produced by Holoeye and Meadowlark Optics. The SLM series manufactured by Holoeye [6] includes a GAEA microdisplay for purely phase modulation, which has outstanding characteristics: 4094 × 2464 pixels (about 10 megapixels), a resolution of 133.5 lines mm^{-1} (pixel period 3.74 μm), 0.7-inch-diagonal working matrix, and 256 grey levels (8 bit). Its operating speed is rather low: only 24 frames s^{-1}. Nevertheless, using the HDMI interface of version 1.4 and the corresponding Pattern Generator software, one can increase this parameter to 30 frames s^{-1} (however, for a smaller format: 3840 × 2160 pixels). The purely phase Pluto and Leto SLMs with a working frequency of 60 Hz have 1920 × 1080 pixels (HD) with periods of 8.0 and 6.4 μm and screen diagonals of 0.7 and 0.55 inches, respectively. The LC-R-720 SLM for amplitude–phase modulation is characterised by an increased operating speed (180 frames s^{-1}), which is provided by the use of NLC twisted structure.

Meadowlark Optics [7] has proposed to use a one-dimensional grating consisting of 12288 pixels with a period of 1.6 μm and a 0.6-μm gap between the pixels for phase, amplitude, and mixed modulation. This diffraction grating, being fabricated by the LCoS technology, is highly demanded in holography. The grating efficiency reaches 95%, and its resolution may be as high as 500 levels in the range of phase variation from 0 to 2π. In addition, Meadowlark Optics manufactures (256 × 256)- and (512 × 512)-pixel SLM matrices for the same purposes.

Colour images are generally formed using a scheme with three LCoS microdisplays in optical RGB channels (Fig. 3).

Using NLCs with an increased switching rate and the field sequential colour (FSC) method, which is implemented by means of three successively switched on bright RGB LEDs (or laser diodes), Syndiant (United States) has developed a fabrication technology of VueG8 microdisplay for pico projectors suitable also for digital holography [8].

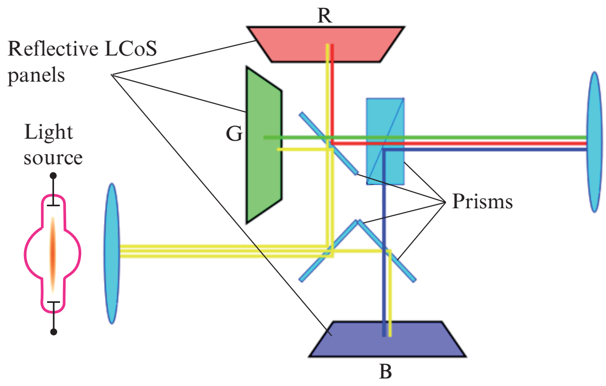


Figure 3. Schematic of the formation of colour images using reflective LCoS panels (https://en.wikipedia.org/wiki/Liquid_crystal_on_silicon).

Figure 4 shows schematic diagrams of the FSC method and the modern method of spatial formation of colours using subpixels. The FSC method suggests operation without subpixels and, correspondingly, without colour RGB filters. Therefore, it provides less structured (smoothed) and twice as bright images; it also has some technological advantages, because a display of the same format requires a three times smaller number of addressed pixels. In addition, since the FSC-LCoS structure is simpler, the design includes elements of electrical rather than optical (more complicated) testing of the LCoS operating capacity. The other parameters (pixel size, filling factor, and optical contrast) are the same for LCoS microdisplays of both types.

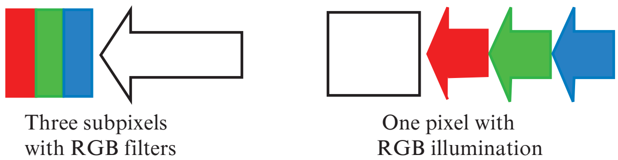


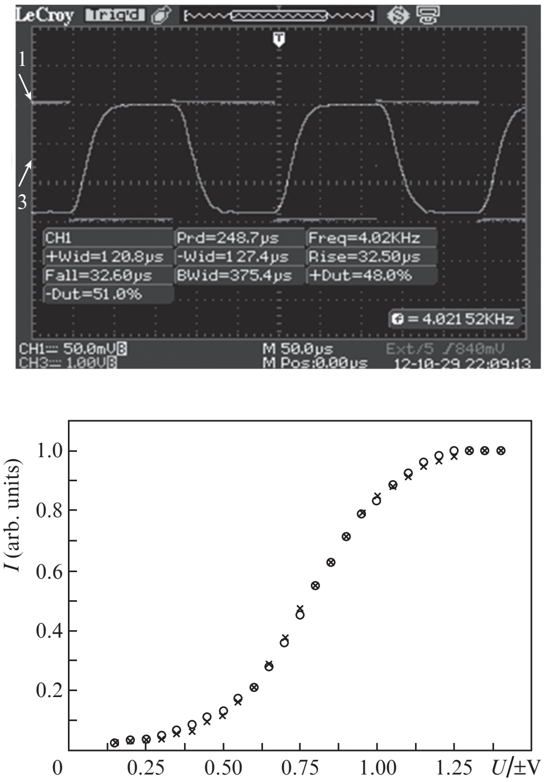
Figure 4. Methods of spatial (on the left) and field-sequential (on the right) colour formation by an image element.

2.3. Microdisplays and SLMs with a FLCoS structure [12–16]

The differences between the microdisplays with ferroelectric LCs and NLC-LCoS structures are as follows:(i) the switching time of FLCs may be several tens of times shorter than that of NLCs and (ii) FLCs are controlled by short bipolar voltage pulses. Hence, the requirements to their fabrication technology are more stringent. However, the CMOS technology, based on the use of a large number of interconnections in a close packing, provides a small pixel size, a low power consumption, and high rates of change of the images formed in FLCs (up to several thousands of frames per second). The technological problem of designing an electro-optical FLC cell with an FLC layer as thin as about 1 μm, which provides cell achromatism in the visible wavelength range, was also successfully solved.

The FLCoS microdisplays, which were developed for the first time by Displaytech (United States), are based on FLC materials with a bistable modulation characteristic. Therefore, to form the grey scale (halftones) and colours, one must use additional modulation of electronic signals, thus converting the high optical switching frequency (several kilohertz) into the corresponding number of colour gradations in bits. As a result, although the images change with a frequency not higher than 240 – 360 Hz, the FSC method with the use of three RGB LEDs can successfully be applied.

An FLCoS microdisplay based on the use of an SLC material with a continuous grey scale, implemented without any additional electronic modulation of signal, is being developed at Cambridge University (United Kingdom) [17]. This material, fabricated at the Lebedev Physics Institute (Russia), makes it possible to form colour images (using, in particular, the FSC method) with a frame rate up to 4 kHz (Fig. 5).



a

b

Figure 5. (a) Oscillogram of the optical response and (b) the modulation characteristic of 1.7-μm-thick electro-optic cell with FLC of the HF-32C composition at a frequency of 4 kHz for a (×) decrease and (○) increase in the control voltage amplitude. Arrows 3 and 1 indicate the zero levels of bipolar voltage pulses and optical response, respectively.

The control circuits in both types of microdisplays satisfy the condition of a zero current balance to avoid FLC irreversible polarisation.

Kopin and Micron Technologies produce several versions of VGA, WVGA, SVGA, and XGA FLCoS microdisplays with a working area diagonal from 0.4 to 0.5 inches [15]. They consume power less than 100 mW and form images with a light flux up to 100 lm. Forthdd (now a division of Kopin) has developed microdisplays of even larger format [12]: WXGA (1280 × 768 pixels, period 13.62 μm), SXGA (1280 × 1024 pixels, period 13.62 μm), and QXGA (2048 × 1536 pixels, period 8.2 μm). They all can work at temperatures from –10 to +65 °C (the storage temperature can be ranged from –40 to +80 °C) and be used as SLMs for amplitude – phase modulation of monochromatic light. In addition, the high-speed (up to 4.5 kHz) bistable QXGA-3DM SLMs were applied as binary (0 or π) phase modulators of coherent light, providing an efficiency of 10 % at a wavelength of 544 nm in the first diffraction order [16].

2.4. DMD microdisplays [5, 18 – 21]

DMD microdisplays, which are fabricated by the so-called digital light processing (DLP) technology (developed at Texas Instruments), belong to the fastest and brightest ones. In these displays, the screen forming an image is a matrix of electrically controlled micromirrors; it is located on a silicon substrate, within which (as in the case of LCoSs), control electronics components are formed (Fig. 6).

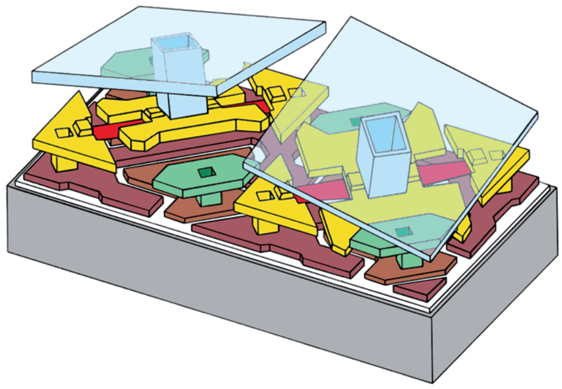


Figure 6. Structure of two display cells of DMD microdisplay (http://www.3dnews.ru/_imgdata/img/2010/10/22/600716/mems-dmd-3.gif).

The principle of image formation in DLP devices is electromechanical rather than electro-optical. When an electric signal is applied to the micromirror cell electrodes, a thin and light micromirror ~10 × 10 μm in size, mounted on a hinge, is deflected by an electrostatic force at a certain angle (e.g., 20°) to one or another side with respect to the hinge (the micromirror occupies the intermediate position in only the inoperative state); the deflection time is about 10 μs. The gap between the micromirrors is narrow: about 1 μm. A light beam reflected from them falls (or does not fall) into the output window (Fig. 7), due to which the optical contrast becomes as high as 10000 : 1. The light that did not hit the window is absorbed in the material, which also provides a reliable heat removal and minimum light reflection, – conditions that are necessary in the case of high reading light power (implemented due to the use of micromirrors).

The grey scale (and colours) in the images are implemented due to the repetition of micromirror deflections with different frequencies. Since the optical switching rate, defined by the deflection time, is rather high, the colour image is formed according to the FSC method, using a white light source and a rotating disk with colour light filters on the light path to the DMD matrix (Fig. 8) or three successively switched on RGB LEDs (they can also be located on the disk). Another way is to use three DMD matrices in three optical reading channels and combine three mono-

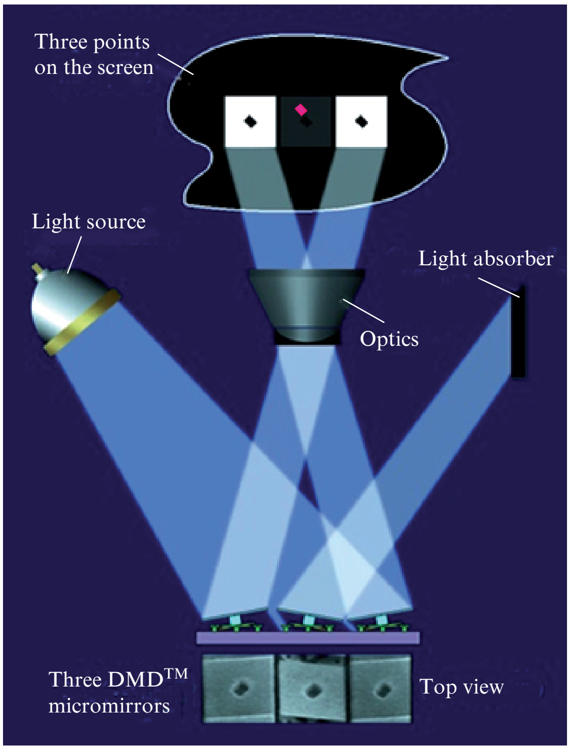


Figure 7. Schematic diagram of the image formation using three micromirrors [19].

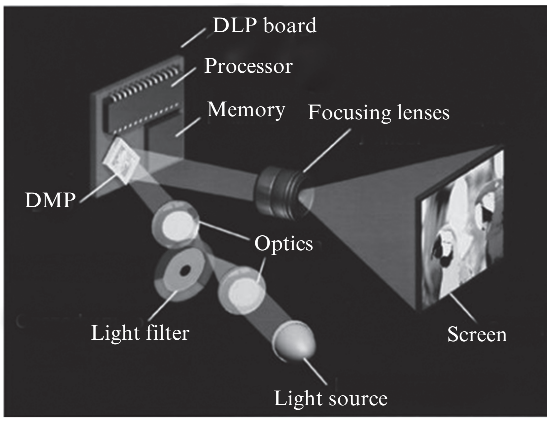


Figure 8. Schematic diagram of data display in a single-matrix DLP projector [19].

chromatic images. The optical scheme of this three-matrix (three-chip) DLP projector is even more cumbersome, but it can operate with a higher speed, larger number of gradations (colours), and higher light power; therefore, it can be used to project images onto large screens (including movie screens) and in other applications.

Currently, many electronics companies use the DLP technology to produce video projectors for most diverse purposes; examples are miniature helmet and screenless displays, SLMs, smartphones, pico projectors, and auditorium and cinema video projectors [20]. The projector format changes from VGA (640 × 480) to HDTV (1920 × 1080) and WQXGA (2560 × 1600), and the light flow varies from 20–50 to 4000 lm.

Texas Instruments continues to manufacture and improve the key element of these devices: DMD matrix [21]. One of latest developments in this field is the DLP4500 chip with the following characteristics: a resolution of 1280 × 768 pixels, a period of 7.6 μm, and frame rates of 120 Hz for 8-bit data and 4225 Hz for binary data; the matrix is addressed at a rate of 4.4 Gb s^{-1} and consumes a power of 407 mW. The latest chip DLP4710 has a resolution of 1920 × 1080 pixels (HDTV), a period of 5.4 μm, a diagonal of about 12 mm, and a micromirror deflection angle of ±17°. The display contains, along with this chip, a DLPC3439 controller and DLPA3000/DLPA3005 PMIC/LED drivers. The DLP3310 chip, which is controlled by DLPC3437, is the smallest micromirror display with 1080 rows; its diagonal size is as small as 0.3 inches. The parameters of the latest DMD arrays indicate that the problem of decreasing the pixel size has been successfully solved in DLP devices (the minimum matrix period had been 17 μm for many years). Correspondingly, the micromirror deflection rate and frame rate increased: they are now close to 8 kHz for binary images.

3. Comparison of microdisplays

It is convenient to perform a comparison using Table 1, where the characteristics of the above-considered microdisplays are presented qualitatively, using plus signs: the larger the number of pluses, the better the display is (by analogy with [4]).

The main properties and advantages/drawbacks of the microdisplays listed in the table are fairly clear. The HD format has been achieved and overcome in microdisplays of almost all types. The devices based on the FLCoS (GS) structure and DMD array are characterised by the highest operating speed. These displays (especially the DMD-based ones) are the brightest ones; in addition, the polarisation of the input light beam is of no importance for amplitude modulation in the DMD array. An amplitude modulation with a highest optical contrast is implemented in DMD; however, it calls for a number of complicated electronic and optical tricks.

The phase only light modulation, which is highly demanded for in holographic applications, can be most easily implemented in NLC-based devices (using the electro-optical effect of controlled birefringence); however, these devices are rather slow (their conventional operating speed is 60 Hz). The microdisplays based on the LCoS structure are characterised by a wide range of NLC operation modes and can spatially modulate light in the wavelength range from UV to far IR, acting as an active dynamic optical element. Some innovations in the LCoS design and the optical reading scheme allowed one to reduce the power consumption and made microdisplays portable, more comfortable for scanning, and more convenient for use. The microdisplays based on the FLCoS structure obey the same principles; they can operate without colour filters, and their operating speed is an order of magnitude higher; however, they cannot provide a phase only modulation of light beams to date (although there are prerequisites for it).

In majority of characteristics, the leader is the DLP (DMD) technology; however, it is the most complicated and expensive one: the DMD array is placed on an expensive ceramic housing, whereas only two layers of inexpensive printed circuit board are necessary for the LCoS structure [8];

Table 1. Comparative characteristics of microdisplays.

Characteristic	Microdisplay type					
	AMLCD (CF)	LCoS (CF)	LCoS (FSC)	FLCoS (BR)	FLCoS (GS*)	DMD (FSC)
Optical switching rate	+	+	++	++	+++	+++
Brightness	++	++	+++	+++	+++	++++
Polarised light	+	+	+	+	+	+++
Modulation type	A, Ph	A, Ph	A, Ph	A, A-Ph	A, A-Ph	A, Ph
Electronics complexity	+++	+++	+++	++	++	+
Optics complexity	++++	+++	++++	++	+++	+
Format (resolution)	HD	HD	HD	HD	SVGA	HD
Control mode	A	A, D	A, D	D	A, D	D
Requirements to temperature	++	++	++	+	+	++++
Lifetime	++++	++++	++++	++++	++++	+++
Technology maturity	+++	+++	++	+++	++	+++

Note. CF is a colour filter microdisplay; FSC is a field-sequential-colour microdisplay; BR is a microdisplay with FLC, characterised by binary optical response; GS* are the expected characteristics of the microdisplay with a continuous greyscale FLC; HD is the high-definition format; A and Ph are, respectively, the amplitude and phase modulation types; and A and D are, respectively, the analogue and digital control modes.

the DMD contains a very large number of moving elements, which call for complicated tuning; the number of contacts and buses in DMD is almost thrice as large as in LCoS; one must perform optical testing of elements, which is more complicated than the electrical testing; and, finally, the image reading optics is more complicated and cumbersome in the DMD case. In addition, it is still unknown if the old problem of micromirror sticking, which is typical of small details (note that the pixel size is close to those obtained in LCoS), has been finally solved. The practice will show soon to what extent the high cost of this device is adequate to its declared high parameters and reliability.

4. Applications of microdisplays

Microdisplays, which operate as dynamic SLMs with a small pixel period and phase modulation of light, are most appropriate for digital holography and holographic displays [3].

An SLM with the LCoS structure acts as a matrix of electrically controlled light wave retarders. The LC in the layer may have either vertical or planar orientation; however, the principal optical axis of the LC should be oriented along the light polarisation direction. Examples of application of phase modulation in digital holography are the holographic sensor for determining the object phase distribution in the CCD detector and the holographic lithography for processing 3D forms on a photoresist layer.

Both phase and amplitude LCoS modes were used in holographic applications [3, 22]. In the studies performed at the Warsaw University of Technology, one Holoeye Pluto SLM was applied to spatially separate Fourier holograms and to reduce zero-order artifacts. Several SLMs were used to form a complex-value wavefront.

See Real Technologies (Germany) demonstrated a full-colour holographic display with a 100-mm diagonal using the LCoS amplitude version and several SLMs (or a spatial combination of pixels on a single SLM), and a transmissive NLC SLM, which combined two matrix columns in order to form a complete complex function in a single modulator.

It was shown in [23] that the characteristics of the modern tools for spatial modulation of laser radiation make it possible to implement invariant filters with minimisation of the correlation energy in schemes of coherent image correlators in the form of synthesised diffraction elements of two types: a holographic filter, synthesised as a Fourier hologram, and a projection element, obtained by projecting the values of the correlation function onto the complex modulation characteristic. To implement a correlation function with optimisation of the correlation characteristics in a Van der Lugt correlator in the form of synthesised holographic filters, one can use SLMs with a limited dynamic range of transmission representation, because a decrease in the number of modulation levels from 256 to 64 does not change significantly the recognition results. Holographic filter transmission levels can be presented using a binary raster; the number of transferred levels should be no less than 16 in this case. To implement a projection-type filter, one must adapt it to the characteristics of the SLM in use. When synthesising a filter, the consideration of the SLM phase delay improves its discrimination characteristics. The potential of the developed methods in the recognition of various images obtained by aerial mapping has been demonstrated.

LCoS-type microdisplays, which modulate light phase with a high optical quality in the range up to 2π, have been used for a long time in adaptive optics to correct wavefronts, in particular, to compensate for atmospheric turbulences [22, 24, 25]. Despite the low operating speed of LCoS structures with NLC, they were also successfully used as selective wavelength switches [26]. For example, a multifunctional 1×9 switch with introduced loss of 7.6 dB and crosstalk of 19.4 dB (in the worst case) for spatial separation of channels has recently been implemented. These devices were found to provide better control of optical fronts and higher flexibility than high-speed microelectromechanical devices.

Currently, bitwise digital data storage systems are dominant. Unlike in the 1970s, it is not now necessary to record large data blocks in the form of holograms using SLMs. However, due to the progress in the technologies of protective holograms, holographic and diffraction optical elements and filters, and optico-holographic methods of data processing, SLMs are called for again. Liquid-crystal phase SLMs operating in transmissive and reflection geometries (LCoS and FLCoS), produced by Holoeye and Meadowlark Optics, are most appropriate for hologram recording.

Recently, in view of the development of 3D technologies (including digital holography) and improvement of microdisplays, most attention has been paid to the prospects of application of these devices as digital hologram formers rather than data block formers, i.e., as elements for implementing real-time holographic and (simultaneously) interactive displays [27]. Let us estimate the possibilities of achieving this goal, taking into account that the three main limitations inherent in these displays must be overcome: the limitations of the data transfer rate, the hologram formation, and the holographic image projection. These three key factors are considered below.

The projection of large holographic 3D images with a wide viewing angle, high video speed, and complete set of colours requires a very large amount of data. Indeed, for a holographic display with sizes of at least 100 × 100 mm and a diffraction angle of 15° × 15°, one needs a pixel period of 1.18 × 1.18 μm to provide a complete parallax at the red light wavelength (633 nm) (according to the optics equations for calculating the diffraction [25]); thus, the number of pixels should be as large as about 92 × 92 K = 8.5×10^9 pixels. For green (532 nm) and blue (450 nm) light wavelengths, the required numbers of pixels are, respectively, 10^{10} and 1.4×10^{10}. To increase the saturated-colour transfer rate (in united RGB channels) to at least 30 frames s^{-1}, the efficiency must be increased to 3.6×10^{11} pixels s^{-1} [27]. Obviously, with increased values of the hologram size, viewing angle, and frame rate, the data transfer rate will significantly exceed 3×10^{11} pixels s^{-1}. Nevertheless, let at least this value be the target efficiency.

As was shown above, the possibilities of existing SLMs do not make it possible to attain this speed. NLC-based LCOSs with the HD image format may provide no more than approximately 10^8 pixels s^{-1} [8]; LCOSs with binary FLCs (FLCOSs) [16] and DMDs [21] can maintain modulation at a level higher than 20 kHz with a resolution exceeding the HD standard, i.e., provide a speed of more than 3.5×10^{10} pixels s^{-1}. Specifically these two devices from all currently available SLMs have the highest efficiency; at the same time, being binary devices, they both suffer from conjugate images when addressed [27]. The use of FLCs with a grey scale in FLCOSs may increase the pixel array formation rate to 10^{12} pixels s^{-1}; however, the problem of their electric control remains unsolved.

Note that different (point, polygon, image) methods used to calculate holograms, even with a wide application of the fast Fourier transform and parallel calculations on several high-quality graphics processors, cannot provide real-time operation, because their efficiency is less than the declared value (3×10^{11} pixels s^{-1}) by three orders of magnitude [27]. In addition, along with the absence of sufficient amount of data delivered per unit time, another problem to solve is to find the way of uniform distribution of the data from each SLM in space and delivering them where necessary.

Concerning the data transfer rate, it should be 360 Gbit s^{-1} or 45 Gbyte s^{-1} [27]. There is a technology satisfying this condition [28]; however, many developments are still in the early stage. In addition, data transfer standards for SLMs must be developed. The last high-speed standard (PCI-E 3.0,16x) can maintain speed up to 15.75 Gbyte s^{-1} , whereas the speed of the next-generation standards (4.0,16x, must be released in 2017) is presumably 31.51 Gbyte s^{-1}, which is close to the target value. However, the use of a greyscale SLM with a larger size and wider angle requires a data transfer rate an order of magnitude higher; it is expected to be reached in the nearest future using FLCoS with greyscale FLC.

Thus, since the single-channel data input can hardly be implemented in the nearest future, one should consider (as an alternative solution) the use of several channels, each of which contains its own microdisplay, calculates data, and transfers them.

There are several prototypes of holographic systems for highly informative displaying (Table 2). The amount of optical data supplied by SLM is given in the table in terms of pixels s^{-1}, with allowance for the image quality (bit $pixel^{-1}$).

The horizontal-parallax-only (HPO) system developed at the Tokyo University of Agriculture and Technology (TUAT, Japan), characterised by an efficiency of 10^{10} pixels s^{-1} (13333 Hz × 1024 × 768), is one of the first systems where a high-speed DMD was successfully applied [29]. The researchers from the National Institute of Information and Communications Technology (NICT, Japan) have developed a system with three LCOS-type SLMs of 8K × 4K format, operating at a frequency of 60 Hz [30]. A system developed at the Agency for Science, Technology, and Research (ASTAR, Singapore) consists of 24 DMD matrices (panels), each operating at a frequency of 720 Hz and having a resolution of 1280 × 1080 [31]. To date, its throughput (2.38×10^{10} pixels s^{-1}) is the upper limit for holographic display systems.

We should also mention the holographic system developed at the Massachusetts Institute of Technology (MIT, United States), where an acousto-optic modulator (AOM) with a throughput of no more than 10^8 pixels s^{-1} has been used for a long time. However, the latest results show [32] that the throughput of the prototype with the use of 40 AOM channels reaches 4×10^9 pixels s^{-1}. The development of a system consisting of 1250 channels, which can provide a throughput of 1.25×10^{11} pixels s^{-1}, has been declared to begin. Nevertheless, one must take into account that an increase in the number of SLMs (information panels of a multipanel system) not only increases the amount of data introduced but also makes the system more complicated; in other words, it makes necessary to perform a physical

Table 2. Comparison of holographic display prototypes [27].

System	Year of creation	Publication	Amount of input data/10^9 pixels s^{-1}	Number of SLMs	Amount of data per SLM/10^9 pixels s^{-1}
TUAT	2009	[29]	10	1	10
NICT	2013	[30]	6	3	2
ASTAR	2013	[31]	23.8	24	about 1
MIT	2014	[32]	4	40	0.1

alignment of several tens (or more) SLMs and imposes stringent requirements on the distribution systems, such as scanners.

Figure 9 shows examples of data distribution in a multipanel holographic display system [27]. In the conventional integral imaging (CII) scheme, to implement angular fragmentation, each 2D image is projected at a certain viewing angle through the corresponding four-focus imaging system (Fig. 9a). In the case of conventional integral holography (CIH), conventional 2D image sources are replaced with holograms, which record information about the wavefront of reconstructed 3D images (Fig. 9b).

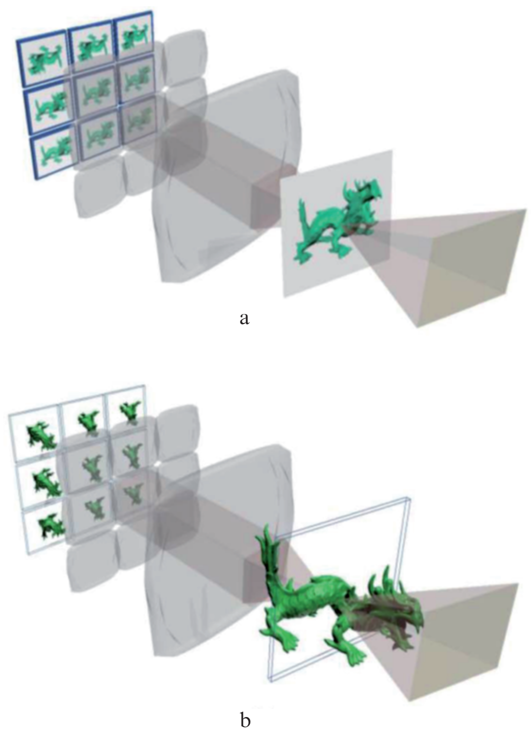


Figure 9. Examples of data distribution in a multipanel system [27]: (a) schematic of conventional integral imaging with panel 2D-image sources and (b) schematic of conventional integral holography with 2D-image sources replaced by holograms.

5. Conclusions

We have considered the characteristics of different microdisplays, compared them, and determined the possibilities of their use as spatial light modulators. The NLC-based SLMs are most appropriate for phase only modulation of light. The SLMs based on a micromirror matrix and FLCOS structure have a maximum throughput.

To demonstrate on-line holographic 3D images, the latter must be formed using SLMs with a very high speed (no less than 10^{11} pixels s^{-1}). Currently, none of microdisplays can satisfy this condition. In this context, the following three approaches [27] appear to be promising:

(i) to continue the development of microdisplays and SLMs with a throughput exceeding the current value by an order of magnitude and more;

(ii) to design multipanel image formation devices based on the existing microdisplays and develop a method for distributing data from each microdisplay in order to accumulate all data on one panel, i.e., in one imaging system; and

(iii) to allow some decrease in throughput and, as a consequence, some deterioration of the visual effect (reduced image resolution, use of one parallax axis, etc.).

The second approach can be implemented more rapidly than the first one, for example, by aggregating more than 10 high-speed (above 10 kHz) HD DMD matrices and using efficient data distribution. At the same time, the third approach does not conflict with the first and second ones; hence, it also has a right to exist. For example, a holographic HPO display (without a vertical parallax) with sizes of 100 × 100 mm, diffraction angle of 15°, renewal frequency of 30 Hz, and a complete colour set can theoretically be implemented using one modern high-speed HD DMD matrix. Another way is to limit the matrix format but apply a system composed of several panels.

From the point of view of efficiency of using visual data, it is expedient (when possible) to direct these data only into observer's eye rather than the entire environment. To implement interactive holographic displays operating in real time, the helmet holographic projection display can be integrated with augmented (AR) or mixed (MR) realities. In this case, the SLM, hologram calculation procedure, and data transfer can satisfy the requirements to 3D viewing using the existing technology. The problems to solve for these holographic helmet displays are similar to those for the existing stereoscopic helmet displays: increase in the field of view, possibility of tracing user's position, and development of a more compact and light system [27].

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