Invited Paper

Advances in Liquid Crystal on Silicon (LCOS) Spatial Light Modulator Technology

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ABSTRACT

LCOS (Liquid Crystal on Silicon) is a reflective microdisplay technology based on a single crystal silicon pixel controller backplane which drives a liquid crystal layer. Using standard CMOS processes, microdisplays with extremely small pixels, high fill factor (pixel aperture ratio) and low fabrication costs are created. Recent advances in integrated circuit design and liquid crystal materials have increased the application of LCOS to displays and other optical functions. Pixel pitch below 3 µm, resolution of 8K x 4K, and sequential contrast ratios of 100K:1 have been achieved. These devices can modulate light spatially in amplitude or phase, so they act as an active dynamic optical element. Liquid crystal materials can be chosen to modulate illumination sources from the UV through far IR. The new LCOS designs have reduced power consumption to make portable displays and viewing elements more viable. Also innovative optical system elements including image and illumination waveguides and laser illuminators have been combined into LCOS based display systems for HMD, HUD, projector, and image analysis/surveillance direct view monitor applications. Dynamic displays utilizing the fine pixel pitch and phase mode operation of LCOS are advancing the development of true holographic displays. The paper will review these technology advances of LCOS and the display applications and related system implementation.

Keywords: LCOS, liquid crystal on silicon, spatial light modulator, SLM, microdisplay, projection display

INTRODUCTION

Microdisplay performance has evolved with the growth of semiconductor technology to fabricate small display pixels and create high resolution arrays of the pixels. This has been complemented by the ability to control and address the pixel arrays with high bandwidth signal capability. In a more general sense microdisplays are spatial light modulators (SLM) that can modulate the amplitude, phase, or polarization of light waves spatially and temporally. Microdisplay technologies that are presently most commercially important are: 1.reflective LCOS (Reflection mode LC on silicon); 2.AMLCD (Transmissive mode active matrix LC); 3.MEMs/DMD (microelectromechanical system/digital micromirror display); 4.OLED (organic light emitting diode display).

In this paper reflective 2D array LCOS technology will be summarized. A comprehensive review of LCOS spatial light modulators and applications was published in 2012[1]. LCOS combines the advantages of a silicon IC backplane with a wide range of LC operational modes. This results in the highest resolution combined with the small pixel size and the highest fill factor (active area of the display surface) compared to MEMs and AMLCD. The light is not limited by transmission through the panel as in AMLCD or limited by the emitting properties of OLED so that high light levels and efficiency can be attained. LC technology can modulate the phase and polarization of light directly. The state of the art of LCOS has advanced on the advancements of IC and LC technology which has provided development from a wide range of companies. Finally LCOS is cost effective in production often using IC backplane fabrication with non state of the art design rules.

Broad application range projection systems based on LCOS, AMLCD, and DMD started in the 1990s and have continued in large screen home and commercial applications ever since . The growth of the LCD flat panel size

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effectively eliminated the potentially large consumer RPTV market for LCOS, AMLCD and DMD in the mid-2000s. Now for very high performance large screen applications in digital cinema, planetaria, and simulators DLP™ and LCOS projectors are dominate. These projectors are predominately based on 3 channel RGB configurations to maximize image quality. At the other end the present growing demand for ultra compact projectors and displays using a single full color channel and new industrial SLM applications has opened new avenues for market growth for the three technologies and the newer OLED. In this competitive arena LCOS advancement described below promises to keep this technology viable in the future.

LCOS TECHNOLOGY

2.1 LCOS Configurations

2.1.1 Two predominant LCOS drive modes are used for nematic LC configurations [1]:

Analog Drive: In this case an analog voltage is applied directly to the LC at the pixel mirror. The pixels are addressed progressively row by row and not loaded simultaneously. In this way latency is minimized. Drift and balance of analog voltages at pixels must be compensated for. Field inversion, required for charge balancing in the LC material, occurs at 1-2X of frame rate. The stability of the signal level over a frame is advantageous for short illumination pulses and there is no digital flicker over the frame time as is possible in the digital drive. LC modes hybrid twisted nematic (HTN) and vertically aligned nematic (VA) are used for polarization rotating (amplitude) mode display applications. Phase mode LCOS configurations use nematic modes where polarization is not changed giving a pure retardance of the illumination light.

Digital Drive: With a digital drive a pulse width modulation (PWM) encodes gray levels into a series of binary pulses with frequencies of several kHz. In implementation the pulse width is not varied but the encoding is done with a sequence of bits. The bits of the sequence have individual duration selected to minimize digital artifacts. The LC material has limited rotational viscosity so it responds to an average of the pulses that represent the programmed gray level. The digital drive is more stable and reproducible than the analog drive. Supermodulation (high frequency digital flicker) is possible to varying degrees depending on digital pulse arrangement and LC parameters. Field inversion takes place at the kHz drive frequency. Hybrid analog /digital drive schemes have also been proposed.

2.1.2 Dominant non nematic LC Modes:

The most developed mode available today is based on ferroelectric liquid crystals.[2][3][4] The ferroelectric LC mode uses a smectic LC material that requires unique surface alignment conditions. The ferroelectric modulation of the LC has a time constant of microseconds and is operated in a digital drive binary pulse mode.

2.2 Performance

The present level of performance of LCOS microdisplays is summarized below:

a. Pixel pitch: Pixel pitch at 4 µm is under active development.
b. Inter pixel gap: The spacing between pixel mirrors is now at 0.2 µm. This gives aperture fill factors of ~ 93%.
c. Resolution: Resolution of 4K x 2K with a pixel pitch of 6.8 - 8.5 µm has been in production by Sony and JVC since the early 2000s. 4K x 2K devices under development will be at ~4 µm pitch. JVC and NHK have demonstrated 8K x 4K LCOS devices at a pixel pitch of 4.8 µm. [5]
d. Display diagonal: Display diagonal range from 0.17 to 1.3 inches with the larger devices used for projection of greater than 20K lumens.
e. Contrast Ratio: With birefringent compensation of low off-state tilt LC VA 3 channel configuration and surface planarization contrast ratios of ~100K: 1 have been produced.

f. Illumination energy density: Luminous densities of greater than 2000 lumens /cm^2 on the microdisplay can be achieved. Effective heat sinking is possible because the reflective mode of operation allows the entire silicon backplane to be contacted.
g. Efficiency: Typical light throughput is 70-80% of the polarized input.
h. Response time: Response time (rise and fall) of ~ 1 msec gray level to gray level
i. LC Storage: -50 C to 100 C
j. LC operation: -20 to 80 C

Figure 1 shows photograph of LCOS microdisplays. Figure 2 shows current amplitude mode LCOS microdisplays reported.

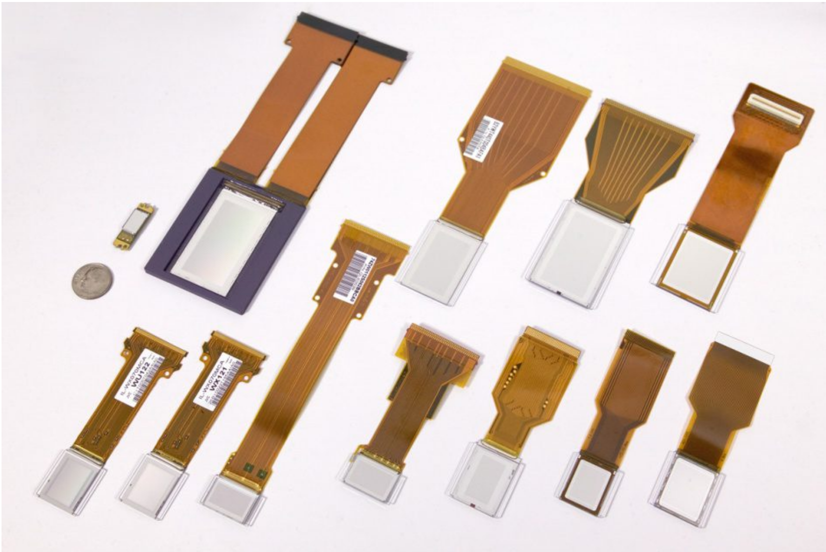


Figure 1. Photograph of LCOS microdisplays (JVC D-ILA™)

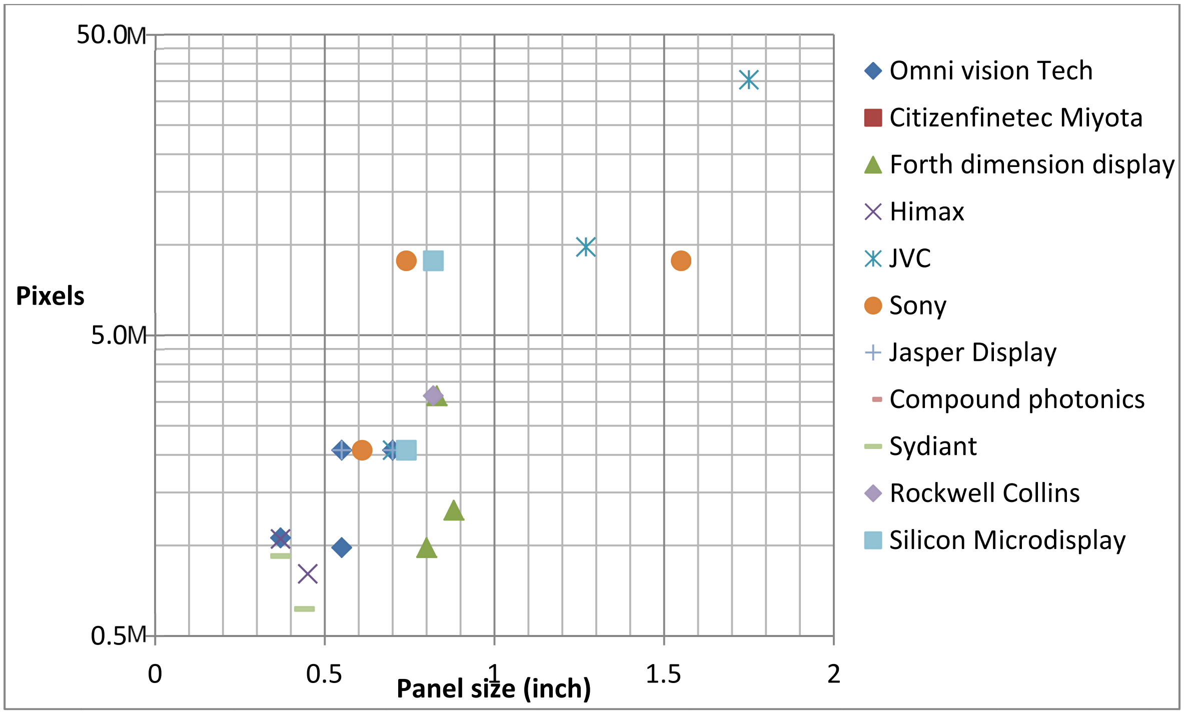


Figure 2. Current reported LCOS microdisplay total pixels as a function of panel diagonal

FUTURE DEVELOPMENT

3.1 Liquid Crystal Materials

Submillisecond response time: The University of Central Florida has reported the development of submillisecond response in a VA mode LC using high Δn, high T_c fluorinated materials. [6] They have also reported sub millisecond response of polymer stabilized blue phase liquid crystals in a reflective SLM configuration. [7]

Alignment: Kent State University researchers have studied the issues of achieving pixel below one micrometer. [8] Their work studies the effect of the fringing field between pixels and the effects of LC design parameters in terms of diffraction efficiency. They will be able to use fully accurate 2D modeling of the electric field profile and resulting director configuration and phase profile, to assess the diffraction efficiency as a function of pixel size, cell gap, electrode gap, and for particular LC modes that can be considered. Figure 3 shows an example of the modeling of LCOS devices.

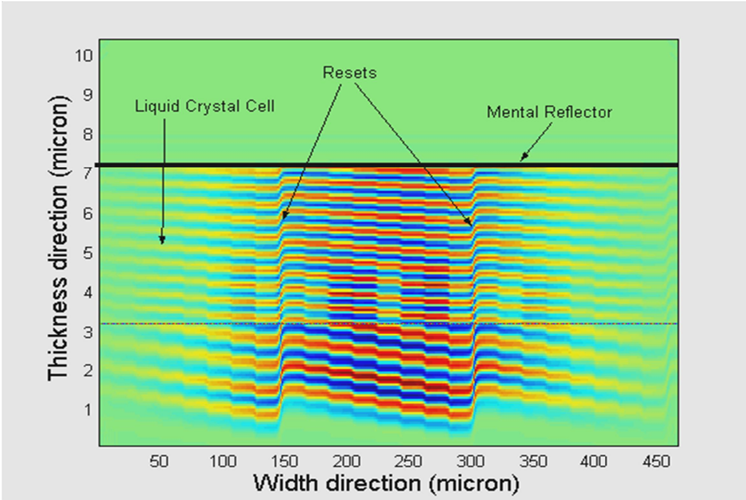


Figure 3. An example of modeling LCOS devices of for beam steering devices

REPRESENTATIVE APPLICATIONS

4.1 Amplitude Mode

4.1.1. Head Mounted Display (HMD)

The combination of an LCOS SLM with a holographic waveguide has opened the path to advanced HMD designs. Examples are the Q Sight of BAE Systems [9] and the Scorpion of Thales [10].

4.1.2. Pico Projector

Imagine Optix had developed 2 reference designs for LCOS pico projectors. [11] Figure 4 below shows their design of the pico projector engine using LED light soure which provides 11.25 lumens/watt output effeciency.

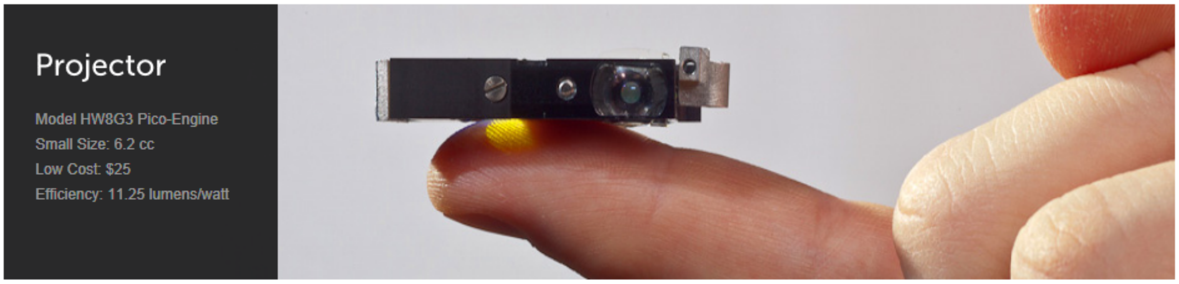
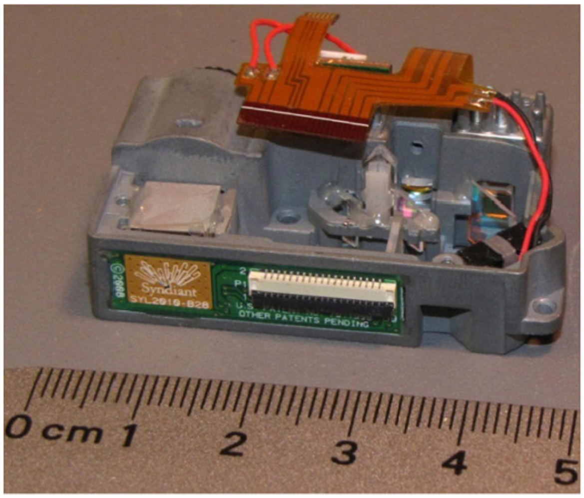


Figure 4. LED LCOS pico projection engine (ImagineOptix)

Syndiant has also published extensively on pico projectors using laser sources [12] Figure 5(a) show picture of their laser pico projector engine. The advantage of using laser light source is due to its low etendue and thus higher output efficiency. The prediction of the lumens/watt trend for laser pico projector is shown in Figure 5(b), assuming improvements are made in the rest of the optical engine. Speckle issue in laser projector has been able to reduce by dynamically diffusing the laser beam electronically or electromechanically. Laser speckle reducers are commercially available.[13]



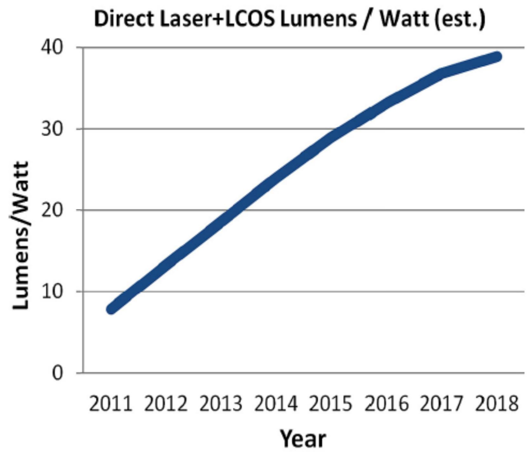


Figure 5. (a) Laser LCOS projection engine. (b) expected lumens/watt trend for Laser LCOS [12]

4.2 Phase Mode

In the phase mode the LCOS SLM acts as a voltage controlled variable retardance waveplate array. Either parallel aligned or vertically aligned LC configurations are possible. (In amplitude mode used for projection displays the extraordinary axis of the LC molecule is aligned 45° to the direction of the light polarization. This allows rotation of the polarization of the light by 90°.) In the phase mode the extraordinary axis of the LC is aligned with the light polarization direction so only the phase of the light is changed. It is also possible to get "phase-mostly" operation from a twisted nematic LC in conjunction with QWP.

4.2.1 Applications of phase mode LCOS[1]

Phase modulators have applications for a wide variety of applications in measurement systems, microscopy, telecommunications, and digital holography. Examples are:

a. Holographic sensor for determining the phase distribution of an object in a CCD detector.
b. Holographic lithography for processing 3D shapes in photoresist
c. High power laser ablation for microstructuring
d. Microscopic applications including structured illumination microscopy, optical tweezing, phase contrast microscopy, superresolution microscopy, point spread function mode engineering

4.2.2 Electro-Holography for true 3D display

Holographic applications have used both phase and amplitude mode LCOS as a single modulator. A full color 2D projection system was demonstrated by Light Blue Optics [14] using a Forth Dimension Displays ferroelectric SLM. The system was configured as a projection keyboard. The high frame rate of the ferroelectric LCOS reduced speckle noise. The Warsaw University of Technology has applied spatial division of Fourier holograms on a HOLOEYE Pluto SLM to project a full color image. [15] They advanced optical techniques to reduce speckle and the zero-order artifact.

It is advantageous to change both the phase and amplitude of an incoming wavefront simultaneously creating a complex-value wavefront. This cannot be accomplished directly in a single cell because the amplitude and phase values cannot be chosen independently. Methods to create the complex value have used multiple SLMs or spatial pixel combinations (2 phase, 3 amplitude, 4 mixed mode twisted nematic). [16] See Real Technologies demonstrated a 100 mm diagonal full color holographic 3D display using an amplitude mode LCOS SLM to create the complex wavefront. [17] SeeReal also demonstrated a transmissive LC modulator that combined 2 columns of the array to create a full complex function in single modulator.

4.2.3 Telecommunication

The LCOS modulator has been used in fiberoptic telecommunication networks. HOLOEYE Photonics produces a Pluto™ phase modulator operating at 1550 nm. [18]

4.2.4. Simulation

JVC has developed simulator projectors based on their D-ILA™ technology. They have used a temporal electro optic pixel switch to improve the resolution of a basic spatial array of pixels. [19][20] Rockwell-Collins has a RGBK 4 LCOS projector that achieves a 10^6:1 sequential contrast ratio. [21]

Figure 6. Photographs of JVC Kenwood LCOS HUD shown at the Consumer Electronics Show.

4.2.5. HUD

LCOS based head up displays are under development for vehicle and avionic applications. JVC-Kenwood demonstrated a LCOS HUD concept with brightness of 10K cd/m^2 and a resolution of 800x600 pixels.

SUMMARY

Over many LCOS technology has continued to evolve to meet new applications for displays and a wide variety of scientific and industrial/commercial applications. The key technologies, IC and LC continue to be major development areas around the world. LCOS takes advantage of this and provides a basis where many companies can contribute designing and manufacturing the LCOS SLM components.

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