Flexible SLM technology finds many applications

Could your application benefit from a spatial light modulator? **Andreas Hermerschmidt** of German SLM specialist Holoeye Photonics describes what options you will find on the market today, how these can be exploited and what performance levels you can expect.

Spatial light modulators (SLMs) are essentially adaptive optical devices that manipulate light that is transmitted through them or reflected by them. This manipulation can be with respect to the amplitude, phase or polarization of the incident light, and the SLM controls the corresponding spatial positions independently.

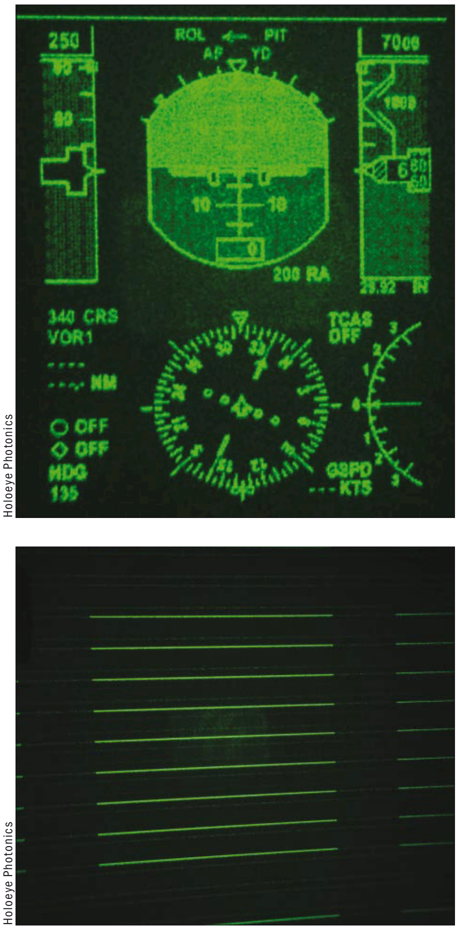
The constant development of SLM technology has opened up many new applications. One contributing factor is the fact that an SLM can be addressed by simply connecting it to a computer as an external monitor. In our opinion, SLMs will soon be OEM components, not only for conventional video projection applications based on amplitude modulation, but also in applications based on phase modulation, such as holographic optical tweezers, holographic optical storage media and even holographic image projection for head-up displays.

In many systems, the SLM acts as an optical digital–analogue interface and active matrix addressing is common. Being dynamically addressable, SLMs can be thought of as a switchable alternative to optical components, such as projection slides, apertures, lenses, diffraction gratings, beam splitters and waveplates. This opens up a wide range of applications where it is convenient to replace a static component with an SLM.

An SLM-based dynamic replacement of an optical component will have somewhat different properties to its static counterpart. These differences depend on the application parameters and the way that the SLM is implemented.

Apart from niche applications, there are two common SLM implementations. The first is a micromechanical SLM that uses arrays of movable micromirrors. The second is an electro-optical SLM that, for example, uses various types of liquid crystal (LC)-based microdisplays.

Alongside these implementations, SLMs can be distinguished into translucent and reflective devices.



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Phase-modulating SLMs are the ideal choice for displaying computer-generated holograms (top) and patterns with low fill factors (bottom).

Micromechanical SLMs

Micromechanical SLMs, which are based on moving reflective parts, are only available as reflective devices. For image projection, the SLM needs to represent an object of spatially variable transmittance or reflectivity. A micromirror, which has a fixed reflectivity, can only provide a variable reflectivity by switching between two tilt positions representing an on and off state in time intervals that are much shorter than the typical time intervals of observation. In this way, binary pulse-width modulation of the addressed signal is used to eventually obtain a variable amplitude modulation.

In image projection applications, the observation bandwidth is limited to approximately 100 Hz. This means that the switching speeds of today's commercially available movable micromirror arrays are sufficiently high to produce greyscale, or even colour images, at high bit depth using a single SLM if a time-sequential RGB illumination source is used.

When phase modulation is required, the averaging approach used for amplitude modulation does not work. This is because the diffracted signal in the plane of interest averages in a different way than the phase modulation itself.

The solution comes in the form of arrays of movable micromirrors. Such mirrors move back and forth on piston-like holders and introduce a variable optical path delay. However, a precise and stable control of the mirror positions is needed and this is a challenge for the technology. This is one reason why the available phase-modulating micromechanical SLMs still have a limited number of pixels.

The reflectivity of mirrors at small angles of incidence is usually almost independent of the polarization state of the incident light. On one hand this means that micromechanical SLMs offer a polarization-independent performance but on the other, polarization modulation cannot be implemented by this type of SLM.

In contrast, electro-optical SLMs based on LC microdisplays do show a polarization-dependent performance. They are most effective when used with a polarized light source. Unpolarized sources would have to be polarized first, which results in a loss of energy. It is worth adding that the polarization-dependent performance can be used to change the polarization of light by implementing, for example, a polarization rotator with a spatially variable rotation angle. ▷

Liquid-crystal SLMs

LC-based devices are available as translucent and reflective components. In translucent varieties, the LC material is sandwiched between two transparent ITO electrodes. It is often more straightforward to integrate a translucent SLM into your existing optical set-up than a reflective SLM.

However, translucent SLMs have a lower optical fill factor (OFF) than their reflective counterparts. This means that a smaller portion of the surface area is used to modulate the light mainly because some of the inter-pixel space is used for the circuitry that addresses the individual pixels, reducing the light efficiency of the device.

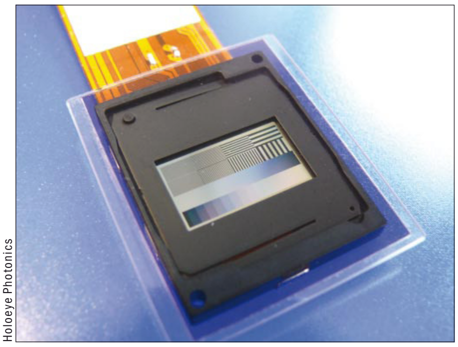
Reflective LC-based SLMs use liquid crystal on silicon (LCOS) devices that have an OFF of around 90%. In addition, the reflectivity of the so-called "back plane" that replaces one of the transparent electrodes is high, and in turn the light efficiency of reflective devices is considerably higher.

The two most common choices of LC materials are ferroelectric and nematic. LC cells based on ferroelectric materials can exploit just two different molecular orientations, which restricts the cell to binary modulation of the light field. However, the switching time between the two molecule states is short and signals can be displayed at kilohertz frequencies. If amplitude modulation of a greyscale display at around 100 Hz is desired then binary pulse-width modulation is an option. For phase modulation, two true phase states are available at high switching speeds.

Nematic LC materials are used in different cell configurations. The orientation of the molecules, which tend to align parallel to each other, can be controlled by using director plates as the top and bottom covers of the cell. If the top director plate is rotated by 90° with respect to the bottom plate, the molecules form a helix structure and are referred to as twisted nematic (TN) cells. When a voltage is applied between the transparent electrodes of the cell, the molecules take a voltage-dependent position and tend to align parallel to the electric field (see figure 1).

Polarized light passing through a TN cell follows the helix of the molecule axes and a polarization change is observed. This means that a TN cell sandwiched between two polarizers can be used as an amplitude modulator, even for white light sources. Here no pulse-width modulation is required to obtain the intermediate greyscale transmission values between the "black" and "white" states.

The switching time of nematic LC materials ranges from 1–15 ms. This is sufficient for image projection applications at typical video frame rates and even for colour field sequential RGB applications. There is also an effect on the phase of the transmitted light in LC cells (see figure 1). The optical phase delay (OPD) for light travelling through individual TN cells is voltage dependent and the cell can be used as a phase modulator.



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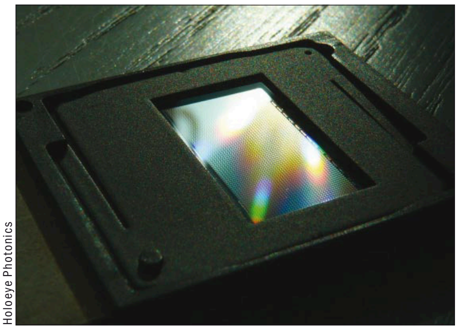

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A reflective microdisplay using a VAN cell (top) is an ideal amplitude modulator. The surface of a phase-only modulating LCOS-based SLM (bottom) appears to carry a structure due to the diffraction effects for one polarization direction of incident light.

Vertically aligned nematic (VAN) cells (or similar cells with an electrically controlled birefringence (ECB) mode) comprise two parallel director plates. The molecules' axes are parallel for all voltage levels and the cell therefore acts as an optical retardation plate (or waveplate) with variable retardation. This makes VAN cells ideal for use as amplitude modulators, phase modulators and polarization rotators.

To provide amplitude modulation, the VAN cell is used as a retardation plate with an incident polarization of 45° with respect to the optical axis and voltages producing OPDs from zero to half of a wave. At maximum voltage, the cell performs as a half-wave plate and rotates the polarization by 90°. It is then straightforward to use the SLM as an amplitude modulator with additional polarizers.

When using the VAN cell as a phase-modulating SLM, the incident polarization should be polarized parallel to the optical axis and the voltages can then introduce

OPDs ranging from zero to a full wave, corresponding to a phase modulation of 2π. This means that the required phase delay is twice as high as that of an amplitude modulator. It is for this reason that phase modulators, which require thicker LC cells, are still uncommon.

In order to use a VAN or ECB cell as a polarization-rotating SLM, it should have a phase modulation range of 2π and be sandwiched between two quarter-wave plates that have their optical axis rotated at $-45°$ and $45°$ with respect to the optical axis of the SLM. Such a set-up is a true polarization rotator, in the sense that the rotation happens for all states of incident polarization, even elliptical, and the angle of the rotation is controlled fully by the phase delay of the SLM.

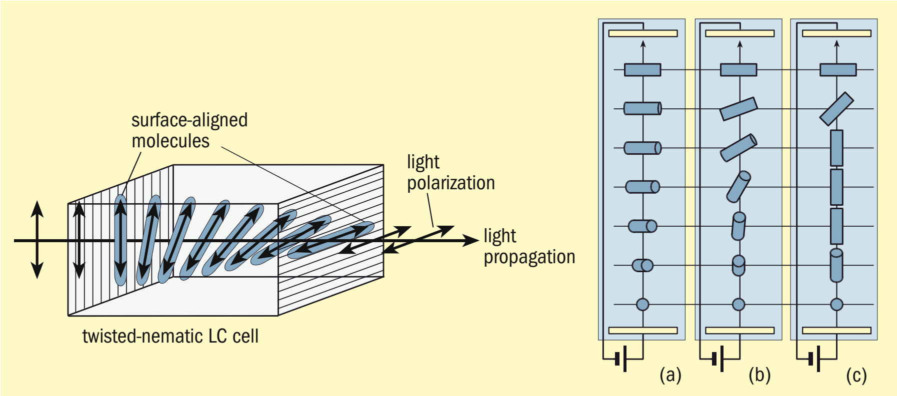

Fig. 1: when a voltage is applied to the electrodes, the molecules align parallel to the electric field.

Consider your application

Parameters such as power levels and wavelength dictate how micromechanical and electro-optical SLMs are used in specific applications. For example, as yet, there are no LC-based SLMs that operate at wavelengths below 400 nm.

Other important parameters are the number of pixels and the pixel size. The number of pixels should usually be as high as possible and today SLMs with up to 1920 × 1200 pixels are available. Smaller pixel sizes are advantageous for phase modulation and pixel sizes have been reduced to 10 µm for 2D pixelated MEMS devices and around 4 µm for LCOS devices.

For amplitude modulation, the contrast that an SLM (including the polarizers) can produce is an essential parameter and should be above 10 000:1. For phase modulation, it is essential that a phase shift of 2π can be produced for all wavelengths of interest. In general, phase modulation is difficult for white light sources because the OPD an SLM can produce is (almost) constant for all wavelengths, leading to different phase shifts. In some applications, for example the temporal pulse shaping of femtosecond lasers, this can be overcome because light is first decomposed into the individual wavelengths that are then incident on different SLM pixels and modulated with the correct phase shift. □

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