January 2007

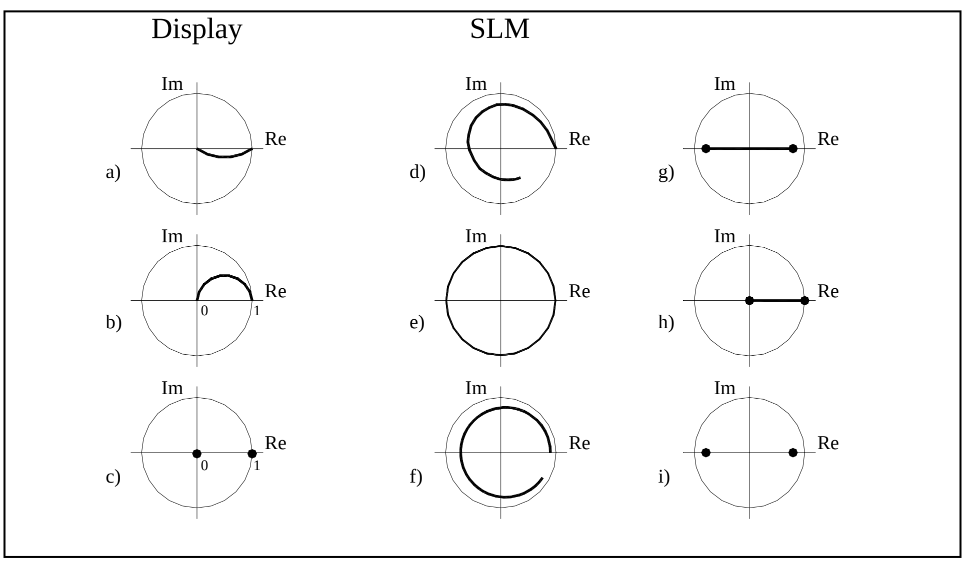
Why Choose BNS?

BNS has been continuously developing liquid crystal spatial light modulators for over 15 years. Through this development process, there has been an advancement of SLM performance not matched by other SLM manufacturers. Such performance enhancement includes:

1) **Sub-millisecond frame loading to prevent phase droop and addressing latency;**
2) **100% fill factor to reduce higher-order diffraction;**
3) **Intra-pixel-pair modulo-2π transitions to maximize space bandwidth product;**
4) **Unique LC modulators**.

Unique Modulators

The active matrix backplanes and drive schemes employed by BNS allow us to use a variety of unique LC modulators in our systems. The operation curves of various LC modulators are shown in Figure 4 where real and imaginary coordinates are used to show the phase and amplitude variation produced by the modulator. As discussed above, we use a very fast load/refresh rate, which eliminates addressing ripple even for sub-video rate modulators. Also, the full multilevel drive signal is applied to the LC modulator within one load cycle, reducing pattern latency. BNS does not rely on the LC modulator to integrate or average the drive signal to form a gray scale response over time as do pulse modulation schemes. Thus, the BNS drive scheme minimizes modulator delay, which is critical in any closed loop system, and maximize gray levels while maintaining low noise.



Operating curves for different electro-optic wavefront modulators: a) amplitude-mostly display (twisted nematic LC), b) complex-amplitude display (parallel-aligned nematic LC), c) binary-amplitude display (binary FLC), d) complex-amplitude SLM (twisted nematic LC), e) phase-only SLM (parallel-aligned nematic), f) nondispersive phase-mostly SLM (FLC topological phase shifter), g) sub-millisecond bipolar amplitude SLM (analog FLC), h) sub-millisecond unipolar amplitude SLM (analog FLC), and i) binary phase SLM (binary FLC).

With LCOS technology, the output modulation is independent of the silicon backplane and is determined by the type of liquid crystal and LC alignment used, as well as its orientation with regard to the input light's polarization. Several types of high-resolution spatial light modulators have been demonstrated using different combinations of these parameters. Some of the more standard are:

- **Sub-millisecond analog amplitude –** full 8-bit images in less than a millisecond (Figure 4h) or real-axis (bipolar amplitude) coverage (Figure 4g) using an FLC modulator;
- **Phase-only** - 0 to 2π (or greater) of optical path difference (Figure 4e) with no amplitude bleed using a parallel-aligned nematic LC;
- **Complex amplitude** - the degree of amplitude and phase produced by a nematic LC modulator is selectively controlled through polarization (refer to Figures 4a and 4d or Figures 4b and 4e).

In addition to the above modulators, which are commonly available, there are other possibilities (some are listed below). These modulators use less conventional liquid crystals cells, require more complicated addressing techniques and generally require higher voltage.

- **Sub-millisecond phase-only –** no amplitude coupling (Figure 2e);
- **Sub-millisecond nondispersive phase-mostly** (achromatic phase shifter) - nearly one wave of phase shift that is wavelength independent (Figure 2f);
- **Polarization-independent phase-only –** phase modulates randomly polarized light (Figure 2e).

Polarization-insensitive modulation is important when the incoming light is unpolarized or randomly polarized. This type of modulation is possible by using a mirror and a quarter-wave retarder to change the polarization as the light makes a double pass through a nematic LC modulator[1]. For example, SLMs have been fabricated such that the parallel-aligned nematic LC acts as a phase modulator first to the vertically polarized light. These SLMs also have a passive quarter-wave retarder covering the reflective backplane with the quarter-wave's optic axis rotated 45 degrees from vertical. As the light enters the device, only the vertically polarized light is phase shifted by the modulator. As the light is reflected by the backplane, the quarter-wave retarder rotates the light by 90 degrees, thus the vertical and horizontal polarizations are interchanged. As the reflected light leaves the device, the vertical polarization, which was the horizontal polarization, is phase shifted, causing both orthogonal polarization components to have the same phase shift.

It is common to use parallel-aligned or vertically-aligned nematic LC to produce phase-only modulation. For these types of devices, the response time of the modulator is normally related to the thickness of the modulator, which is a function of wavelength and LC birefringence. BNS is developing a series of phase-only SLMs that use a high birefringent material ($\Delta n=0.38$). With this LC material, BNS has improved the speed of our phase-only modulators by a factor of three to five times. Operation in the hundreds of hertz is being achieved at visible wavelengths using these new materials. Also, BNS has achieved sub-millisecond response times with a full wave of modulation depth using dual-frequency nematic materials and a high-voltage 256x256 backplane. These nematic LC materials have a frequency-sensitive dielectric anisotropy. For this type of modulator, the molecules are driven into a high-retardance state instead of relaxing back into this state as would a typical nematic LC modulator.

[1] G.D. Love, "Liquid-crystal phase modulator for unpolarized light," Applied Optics, Vol. 32, No. 13, May 1, (1993)

There are ferroelectric liquid crystal (FLC) materials, which provide 50 to 100 microsecond response times. An analog FLC modulator rotates linearly polarized light to produce amplitude-only (0 to 1 as shown in Figure 4h) or bipolar amplitude modulation (-0.7 to 0.7 as shown in Figure 4g) by simply changing the orientation of the output polarizer with respect to the FLC modulator's axis. An amplitude-only FLC modulator driven with BNS' analog 1kx1k backplane generates 24-bit 1024x1024 color images in approximately three milliseconds. With 512x512 and 256x256 backplanes, full 24-bit color image generation is reduce further to 1.2 milliseconds and 0.8 milliseconds, respectively. With bipolar amplitude-only modulation, full complex modulation (i.e. $\mathbf{A}e^{j\theta}$, where A varies from 0 to 0.7 and θ from 0 to 2π) is possible. This is achieved using two pixels to form a macro-pixel with one pixel representing the real values and the other pixel the imaginary values[2].

A very unique LC device is the nondispersive phase-mostly modulators based on high tilt FLC materials. As with all LC modulators, these ferroelectric liquid crystal (FLC) modulators manipulate polarization states to produce the desired output. By rotating circularly polarized light, a nondispersive phase shifter produces a geometric phase shift where red and blue light are equally varied. However, this is not the case for the deformable mirror which produces a phase shift that is proportional to the distance the actuator moves in relation to the light's wavelength. Therefore, blue light is phase shifted more than red light by the optical path difference created by the actuator. With a device that produces a wavelength-independent phase shift, it is possible to build a high-resolution pixilated modulator that phase conjugates broadband light without causing the image to blur from dispersion[3].

Company Profile

Boulder Nonlinear Systems, Inc. (BNS) is an innovative technology company specializing in dynamic liquid crystal polarization control solutions for both laser-based and imaging systems. Company strengths in scientific research and development are leveraged into OEM and standard product offerings targeted for astronomy, biomedical, defense, microscopy, optical computing, optical storage, and telecommunications applications.

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[2] R. Young, *et al*. "Hardware implementation details of a hybrid digital/optical correlator system," in Optical Pattern Recognition XI, Proc. SPIE, Vol. 4043, (2000)
[3] J. Stockley, G. Sharp, S. Serati, P. Wang and K Johnson, "Liquid crystal grating based on modulation of circularly polarized light," in *Diffractive Optics and Micro-Optics*, Vol. 5, OSA (1996)