Core Technologies

Boulder Nonlinear Systems (BNS) is the world leader in developing advanced liquid crystal based devices and systems to control light. Specifically, BNS specializes in two core technologies: liquid crystal on silicon (LCoS) spatial light modulators (SLMs) and liquid crystal polarization gratings (LCPGs).

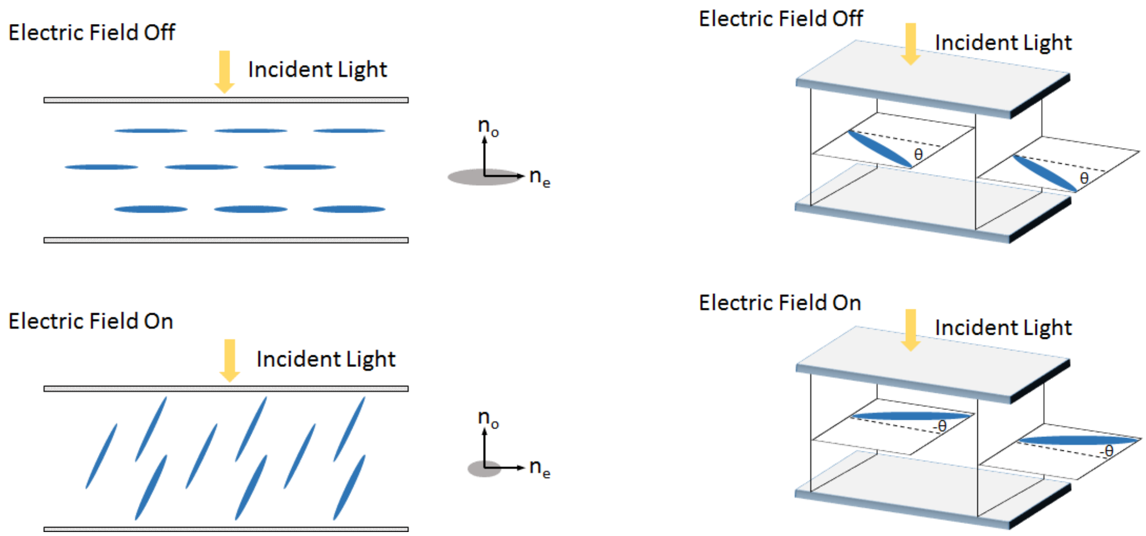
Fast flexible shaping of phase and amplitude with SLMs

Since 1988, BNS has been advancing the state-of-the-art in liquid crystal on silicon (LCoS) spatial light modulator (SLM) technology, which uses an array of independent liquid crystal pixels to shape an incident wavefront. These devices are used to modulate a beam of light in order to add information to it, often in ways that shape, correct, and/or steer it. BNS commonly utilizes two types of liquid crystal: nematic and ferroelectric.

Nematic liquid crystal molecules are elongated and lie perpendicular to the direction of optical propagation in the absence of applied voltage, resulting in birefringence. Application of an electric field can be used to rotate the liquid crystal molecules so that the long axis of the liquid crystal rotates towards the optical axis such that when the liquid crystal and optical axes are aligned, the liquid crystal birefringence is effectively zero. In this manner, a nematic liquid crystal pixel can provide variable analog phase retardance when the incident light is linearly polarized parallel to the liquid crystal axis. Similarly, when the incident light is linearly polarized and aligned at a 45° angle to the liquid crystal axis, only one of the two orthogonal components of the polarization is modulated, and the liquid crystal cell behaves as a variable polarization rotator. When used in conjunction with a polarizer and analyzer, this configuration can be used for analog amplitude control. By incorporating many independently addressable liquid crystal cells in a pixelated device, nematic LCoS SLMs provide the ability to arbitrarily and dynamically shape either phase, amplitude, or both in an incident wavefront, making them extremely versatile devices for beam and pulse shaping, non-mechanical fine angle beam steering, and hologram generation.

Ferroelectric liquid crystals (FLCs) operate in a slightly different manner. In practical FLCs, the liquid crystal molecules are arranged in layers where they are tilted with respect to the layer normal vector such that the angle defines the “tilt plane” and the tilt angle θ determines the optical axis of the liquid crystal. In this configuration, the liquid crystal molecule orientation is capable of rotation along the cone defined by the layer normal vector and θ, which means that applied voltage produces a primarily in-plane rotation of the FLC molecule. As such, FLC modulators can provide analog rotation of the optical axis by 2θ. In this manner, FLC modulators act as fast polarization rotators and can be used to modulate the geometric phase or integrated with polarization optics for amplitude modulation. Compared to nematic LCs, which operate based on varying the apparent refractive index for a given polarization, FLC modulation can be broadly achromatic. Additionally, FLC molecules possess a permanent electric dipole moment and therefore their orientation couples directly to an applied electric field. This provides FLCs with very fast switching speeds, on the order of tens of microseconds.

Nematic Liquid Crystal **Ferroelectric Liquid Crystal**



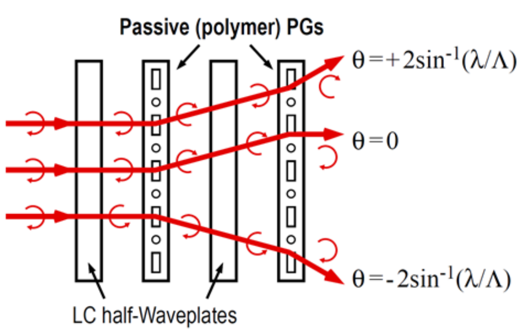
Nematic (left) and Ferroelectric (right) liquid crystal operation. Nematic liquid crystal provides analog phase modulation through out-of-plane rotation and modulation of the effective retardance. Ferroelectric liquid crystal provides switchable in-plane rotation of the optical axis for polarization rotation at fixed retardance.

With over 25 years of experience in SLM development, Boulder Nonlinear Systems is a world leader in SLM technology. The SLM market is primarily made up of devices with backplanes designed for display applications that provide 60 Hz switching speeds at display resolutions. These devices frequently fall short of the performance requirements demanded for advanced applications. In contrast, BNS can develop SLM devices and systems that are specifically tailored to a customer's needs and bring a number of technical advantages. First, BNS spatial light modulators offer the highest frame rates available by using custom liquid crystals, high-voltage backplanes, novel pixel addressing schemes, and low latency drivers. Accordingly, BNS can address SLMs at rates that exceed the liquid crystal response times (up to 24 kHz) to avoid phase ripple for improved phase stability and accuracy and to implement overdriving schemes that improve the SLM frame rate. A second key ability is the high-precision 16-bit analog mode of operation, which allows unmatched control of the incident beam of light. Lastly, BNS has pioneered a number of unique modulation capabilities, such as polarization independent phase modulation, combined phase and amplitude modulation from a single nematic SLM, and achromatic phase modulation. Currently, BNS is pushing each of these capabilities farther while developing new large-format SLM backplanes for greater resolution. In addition to developing cutting-edge custom modulators and SLM-based systems, BNS has developed a standard product line of industry-leading SLMs that are sold through Meadowlark Optics, Inc.

Beam steering and switchable optics with LCPGs

In 2007, BNS began a successful collaboration with North Carolina State University to develop liquid crystal polarization grating (LCPG) switches for non-mechanical wide-angle beam steering. BNS now has a patent pending and exclusive rights for application of these gratings in a beam steering field of use. Passive LCPGs consist of a nematic liquid crystal (LC) film that is surface aligned and UV-cured to present a permanent, continuously varying periodic polarization pattern. Its structure is an in-plane, uniaxial birefringence that varies with position (i.e. $\mathbf{n}(x) = [\sin(\pi x/\Lambda), \cos(\pi x/\Lambda), 0]$, where Λ is the period of the grating). These transmissive gratings efficiently (> 99.8%) diffract circularly polarized light to either the first positive or negative order, based on the handedness of the incident light. Notably, during diffraction, the handedness of the polarization flips. LCPGs have been demonstrated with apertures up to 50 mm and significantly larger apertures can be achieved with appropriate fabrication facilities which are currently under development at BNS. By incorporating fast electro-optic half-wave polarization retarders to control the handedness of polarization incident on a passive LCPG device, BNS can create fast switchable optics with vastly superior size, weight, and power requirements compared to their mechanical counterparts.

Non-mechanical beam scanning can be achieved with an alternating stack of linear LCPGs and electro-optic half-wave retardance switches. Non-mechanical beam scanners provide numerous benefits over traditional gimbaled mechanical scanners due to their vastly reduced size, weight, and power (SWaP) requirements and their ability to perform random access scanning. To achieve non-mechanical beam scanning with LCPGs, a nematic or ferroelectric liquid crystal modulator having an electronically controllable retardance is typically used as the switch, as described above. In this case, the retardance of the LC cell is changed by applying a voltage to either produce a half-wave of retardance or nearly zero retardance through the cell. Thus a half-wave retarder changes the handedness of circularly polarized light while a cell with no retardance does not affect the light's polarization. By controlling the handedness of circularly polarized light as it propagates through the LCPG stack, the light is steered to a selected angle.



A two-stage LCPG beam steering module. In the top ray, the second switch is active and the ray is steered in the positive direction. In the bottom ray, the first switch is active and the ray is steered in the negative direction. When both switches are off, the ray is unaffected.

The LCPGs deflect light by providing a polarization-selective grating pattern. In a similar fashion, BNS has developed a polarization-sensitive lens by replacing the linear grating pattern with a diffractive lens pattern, also known as a Fresnel zone plate. Thus the operation of such a Liquid Crystal Polarization Zone Plate (LCPZP) can be understood in exactly the same way as the LCPG structures described above, as they are merely concentric gratings, circularly symmetric along the propagation direction in which the pitch varies radially from the optic axis, as shown in Figure 2. This radial variation is spherical for a master lens with a spherical surface in the write beam. It can also contain aspheric terms for an aspheric master lens or for multiple spherical lenses of different radii of curvature to simulate aberration-corrected optics.

Analogous to LCPGs, for incident light with one handedness of circular polarization, an LCPZP will cause the incident beam to focus while for the opposite handedness the light passing through the LCPZP the light will diverge. Consequently, the focus of an LCPZP can be adjusted by changing the handedness of the incident circularly polarized light. Thus, by creating a stack of a half-wave switch sandwiched between two LCPZPs, one can create a switchable variable focal length lens, wherein light focused by the first lens is defocused by the second lens when the switch is in the "off" position and the transmitted light is ultimately unaffected by the stack. When the switch is "on", the polarization handedness will flip back to the original polarization in between the LCPZP elements so that the second LCPZP element contributes additional focusing, resulting in a net focusing of the transmitted light.

Boulder Nonlinear Systems is a leader in LCPG-based optics with many years of experience providing custom LCPG-based systems and components to federal, military, industrial, and academic customers. For more information, visit the Research and Development section to learn about specific applications or contact BNS at info@bnonlinear.com to discuss how BNS can provide LCPG solutions for your application.