Beam Steering Using Liquid Crystals

Boulder Nonlinear Systems
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Liquid crystals are frequently used as optical modulators. These materials offer several advantages over mechanical modulators including large modulation depth, no moving parts, low power dissipation, potential for large aperture operation, and low cost. This paper contains a discussion of the considerations necessary for the design and application of liquid crystal beam steerers.

Background

The ability to modulate light with liquid crystal enables many possibilities for photonic devices based on this technology. One such application is the non-mechanical steering of light with liquid crystal based devices. Beamsteerers that employ liquid crystal modulators can be categorized according to the physical mechanisms used to redirect light: refraction and diffraction.

Refractive Beam Steering

Refractive beam deflectors include liquid crystal wedges and devices using double refraction. These devices operate much like a glass prism that refracts light with an index of refraction that is different than that of air. In general, refractive beamsteerers offer high efficiency but small angular deflection. The deflection angle for a wedge is the angle of the wedge divided by the aperture. Consequently this approach yields deflection angles on the order of tens of milli-radians.

For double refraction, or, beam walk-off, the amount of deflection depends on the difference in the ordinary and extraordinary refractive indices, and is typically restricted to a few degrees. Cascading multiple elements in series can improve the deflection angle without drastically reducing the efficiency. Optical phased arrays can be used in refractive mode if no resets are used and the phase ramps continuously across the aperture. Since there are no phase resets, grating dispersion is not present and broadband radiation can be steered.

Diffractive Beam Steering

Diffractive beamsteerers can be implemented with an optical phased array analogous to some radar systems. The diffractive optical phased array can be thought of as a quantized multiple level phase grating. The more phase levels used in the array, the higher the diffraction efficiency. For example, a binary phase grating ideally provides a diffraction efficiency of 40.5% in each of the two first order diffracted beams. For a quantized phase grating using three phase levels the ideal first order diffraction efficiency is 68.4%, while for 4 phase levels, it increases to 81%. For more than four levels the improvement in diffraction efficiency with increasing number of phase levels slows. At 5 levels the percentage of light diffracted into the first order is ideally 87.5% and for 8 phase levels the ideal first order diffraction efficiency is 94.9%.

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Due to the effects of fringing fields between electrode lines, the actual phase profile is not a series of quantized steps but is smoothed such that the device more closely resembles a blazed grating. In addition to the phase profile, device efficiency also depends on the effective fill factor. The effective fill factor is governed by the size of the flyback region (where the phase reset defining a grating period occurs) relative to the size of the grating period. Alternatively, one can attribute lower efficiencies at larger diffraction angles to a finite pixel (element) function. That is, the far field diffraction pattern for the grating written to the device is convolved with a pixel function which envelopes the far field such that efficiency decreases for larger angles. In addition to non-ideal phase profiles, there is an insertion loss that needs to be considered. The insertion loss includes such things as non-ideal mirror reflectivity, Fresnel losses, absorption by and scatter due to the modulating medium and/or structure.

Diffraction Angle

The deflection angle for a diffractive beamsteerer, $_{m}$, is given by:

$$\theta_m = \sin^{-1}\left(\frac{m\lambda}{d}\right) \quad .$$

Here m is the diffracted order (usually only the first order is considered), is the vacuum wavelength, and d is the (variable) grating period. Note that due to the nature of diffractive devices, steering is in general not continuous, though techniques can be used to make the steering appear continuous. A major advantage of diffractive devices is that the addressable angles can be randomly accessed.

An additional advantage of diffractive beamsteerers is the potential for two-dimensional steering using a single device. However, fabrication limitations restrict two-dimensional steering to small angles at this time. One-dimensional diffractive beamsteerers, like the refractive beamsteerers can be cascaded to steer in two dimensions.

The BNS Diffractive Liquid Crystal Beam Steering Array

Boulder Nonlinear Systems (BNS) has had a research and development thrust dedicated to liquid crystal beamsteering since 1991. BNS has developed and recently released a one-dimensional liquid crystal on silicon beam steering product, shown in Figure 1. This product won a Photonics Circle of Excellence award as one of the 25 most innovative photonics products introduced in 2000.

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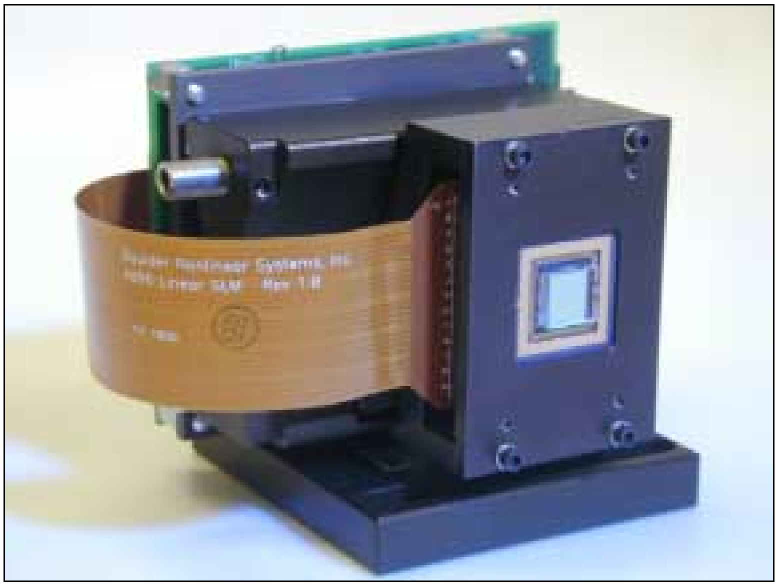

Figure 1 - Optical head for the BNS liquid crystal on silicon optical phased array beamsteerer.

Following are some of the specifications for the VLSI based beam steering device developed at BNS:

- The electrode elements are 1.0 micron wide lines separated by 0.8 micron wide spaces.
- There are 4096 individually addressable electrodes.
- The device can steer to over 8000 different angles, however many of these angles may not be resolvable depending upon the optical path length following the beam steerer and the spot size at the end of this optical path.
- The clear aperture is ~7.4 mm x 6 mm.
- Systems have been delivered for wavelengths ranging from 514-nm to 1.55-µm.

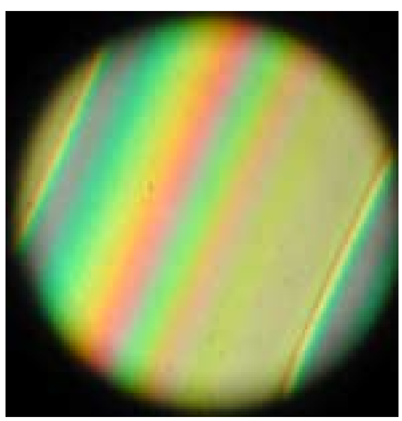

Figure 2 - Photograph of the white-light microscope observation of a BNS liquid crystal beamsteerer utilizing crossed polarizers. The device is being driven with a repeating linear wedge voltage ramp with a pitch of 256 pixels.

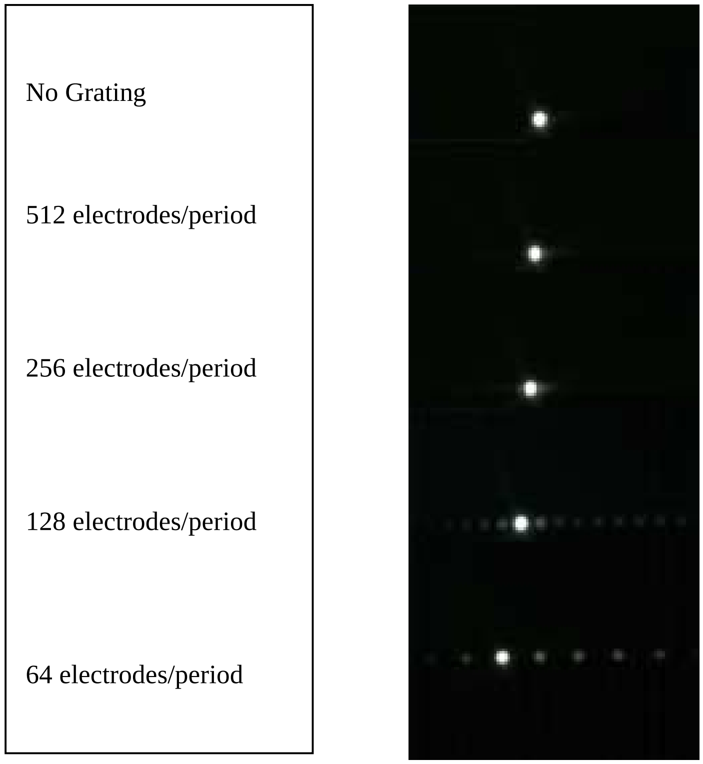

Figure 3 - Several diffraction patterns for various pitched phase wedges applied to the BNS 1x4096 pixel beamsteerer. The phase profile was not optimized, resulting in minor sidelobes for the smaller periods. The wavelength was 1.55-mm with a maximum applied voltage of ±5-V.

Future development goals have been set, which include significantly increasing the aperture of the device (e.g. from 0.74-cm across to a dimension of 18 to 20-cm), and extension to two-dimensional steering. Liquid crystal optical phased arrays are a promising technology for nonmechanical beamsteering. Such devices can be used in diffractive or refractive modes. The 1x4096 pixel array developed at Boulder Nonlinear Systems has demonstrated excellent potential for inertialess beam deflection.

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