

Programmable diffractive optical element using a multichannel lanthanum-modified lead zirconate titanate phase modulator

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We introduce a programmable diffractive optical element based on an electro-optic phased array implemented with a multichannel lanthanum-modified lead zirconate titanate phase modulator. The design and fabrication procedures are outlined, along with an experimental demonstration of the device. Experimental results from a 16-channel device operating with a 2π voltage of 300 V demonstrate selective beam steering. The programmable diffractive optical element allows for efficient, high-speed high-resolution random-access optical beam steering over a continuous scanning range.

Programmable diffractive optical elements that permit fast, efficient, high-resolution random-access optical beam steering are required by numerous applications including two- and three-dimensional displays, programmable optical interconnects, and optical routers. These applications are limited by the current cost and performance characteristics of available random-access scanners. At present, acousto-optic (A-O) Bragg cell deflectors are the most effective choice for high-speed random-access deflection of a laser beam. However, A-O deflectors are relatively expensive, demonstrate only moderate diffraction efficiency, and are difficult to mass produce. Their performance is fundamentally constrained by the inverse relationship between the number of resolvable points N and the random-access time τ of such deflectors.¹ The former is given by $N \propto \tau \Delta f$, where Δf is the useful bandwidth of the acoustic source. For a given source bandwidth, higher-output resolution can be obtained only at the expense of slower access times, effectively holding the combined space-time bandwidths, defined as N/τ , to a constant value for an A-O deflector. Very high-bandwidth A-O deflectors exist, but only for red and infrared wavelengths. Typical performance characteristics of an A-O cell (TeO₂, slow shear mode with 50-MHz bandwidth) that are useful over the visible range are $N = 256$ with a random-access time of 5 μ s, giving combined space-time bandwidths of 50×10^6 points/s.

Development of an alternative high-capacity optical scanning technology with good optical efficiency and alternative design constraints is desirable. In this Letter we introduce and demonstrate experimentally a programmable diffractive optical steering device called a phased-array grating electro-optic scanner (PAGES), which can offer high-speed high-resolution optical scanning with higher diffraction efficiency than that available with A-O cells. The PAGES device consists of a multichannel array of phase modulators implemented in lanthanum-modified lead zirconate titanate (PLZT) that are independently controlled to generate an arbitrary linear phase retardation across the incident optical beam. The amount of lateral shift of the far-field output pattern is directly proportional

to the slope of the linear phase profile, which in turn is programmed and controlled electronically by the electro-optic effect.

A multichannel phased array operating at low voltages and relatively slow speeds (i.e., millisecond response times) has been implemented by the use of liquid-crystal modulators.² Higher-speed performance necessitates the use of electro-optic crystals or ferroceramics, which inherently require larger operating voltages but provide a faster time response (better than 1 μ s). Previous studies demonstrated fast multichannel arrays in slab waveguides that used lithium tantalate and lithium niobate.^{3,4} We choose to use PLZT 9.5/65/35 for phase modulation because of its large quadratic electro-optic coefficient, broadband optical transmission range, fast switching response, and good thermal stability.⁵ Although a demonstration of a high-efficiency binary optical switch using PLZT was reported recently,⁶ our objective is to create an equally efficient but significantly more versatile general-purpose multichannel device capable of multiple switching states and arbitrary wave-front control.

The principle of the PAGES device is similar to that of diffractive optics in which an arbitrary linear phase profile is approximated in a stepwise fashion across the aperture. Following the diffractive optics approach, a maximum phase delay of only 2π is required for any of the modulators, which sets the maximum required voltage for the scanner at $V_{2\pi}$. Because of the step discontinuities some of the incident light energy will be diffracted away from the primary 0th output order, but by proper design of our multichannel phase modulator these losses can be minimized. Thereby, the PAGES scanner can be seen as an electronically controlled diffractive optical phase grating for which the number of resolvable spots N in the output will be proportional to the number of modulators in the array.⁷ The random-access time τ depends primarily on the switching time of an individual modulator and is independent of the number of resolvable spots, in contrast to the case of an A-O deflector. Hence one can increase the combined space-time bandwidths N/τ for a multichannel array by adding modulators to the array and thus increasing N independently of τ . This

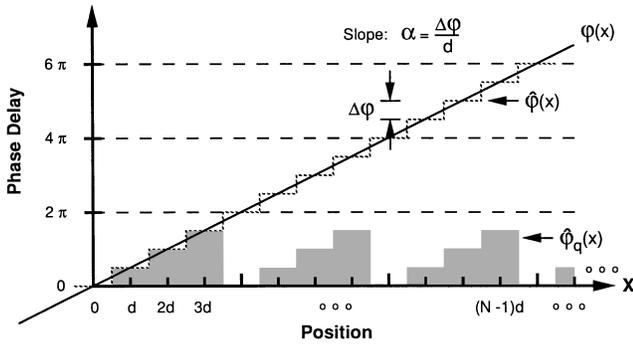


Fig. 1. Mapping a continuous phase distribution $\varphi(x)$ onto a multichannel array of phase modulators.

design freedom is obtained at the expense of a larger device structure and more complex yet realizable driver electronics.

For our initial analysis, consider implementing an infinite one-dimensional linear phase function $\varphi(x) = \alpha x$ with slope α and position x in the array (see Fig. 1). This continuous phase profile represents a thin prism with a transmission function $T_0(x)$:

$$T_0(x) = \exp[i\varphi(x)] = \exp(i\alpha x), \quad (1)$$

where $\alpha = (2\pi/\lambda)\sin\theta$, with θ being the deflection angle and λ the wavelength of the optical beam. The continuous phase function can be mapped onto the array of phase modulators (each of width d) in a stepwise fashion with a constant phase over each modulator. This constant phase is determined by the value of the continuous phase function $\varphi(x)$ evaluated at the center of each modulator. The resulting stepped approximation is designated $\hat{\varphi}(x)$ as shown in Fig. 1, and its transmission function $T_1(x)$ can be described by

$$\begin{aligned} T_1(x) &= \exp[i\hat{\varphi}(x)] = \sum_{(n)} \exp[i\varphi(nd)] \text{rect}\left[\frac{x-nd}{d}\right] \\ &= \text{rect}(x/d) * [T_0(x)(1/d) \text{comb}(x/d)], \end{aligned} \quad (2)$$

where $\text{rect}(x/d) = 1$ for $|x| \leq d/2$ and is zero elsewhere, the comb term represents an infinite array of sampling δ functions centered at each modulator, and $*$ denotes the convolution operator. Finally, note that the actual phase distribution implemented in the multichannel scanner is $\varphi_q(x) = \hat{\varphi}(x) \bmod 2\pi$ (see the shaded profiles in Fig. 1), which is equivalent to $\hat{\varphi}(x)$ under monochromatic illumination. This analysis is valid for any arbitrary phase slope α .

The scanner output lies in the far-field diffraction pattern, which is proportional to the Fourier transform of $T_1(x)$ from Eq. (2) with $T_0(x)$ from Eq. (1), giving the result that

$$\begin{aligned} \mathcal{F}\{T_1(x)\} &= d \text{sinc}(d\nu) \left[\delta\left(\nu - \frac{\alpha}{2\pi}\right) * \text{comb}(d\nu) \right] \\ &= \text{sinc}(d\nu) \left\{ d \text{comb} \left[d\left(\nu - \frac{\alpha}{2\pi}\right) \right] \right\}, \end{aligned} \quad (3)$$

where \mathcal{F} denotes a Fourier transform, ν represents spatial frequency, and $\text{sinc}(d\nu) \equiv \sin(\pi d\nu)/(\pi d\nu)$.

This idealized output pattern represents an infinite sequence of δ functions shifted by $\alpha/2\pi$ and modulated by the constant sinc envelope. The δ functions are spaced $1/d$ apart, each representing a specific diffraction order. The amount of shift of the spectra is directly proportional to the linear phase slope α , and the relative energy of the various diffraction orders is given by the value of the sinc envelope at their respective spatial frequencies.

We built a basic PAGES scanner, using 16 dual-aperture surface electrodes on PLZT 9.5/65/35. This PLZT composition displays a very strong quadratic electro-optical coefficient ($1.5 \times 10^{-16} \text{ m}^2/\text{V}^2$) with minimal residual linear effects.⁵ We fabricated the electrodes on one surface of a 300- μm -thick PLZT wafer, using vacuum-evaporated chrome gold, standard photolithographic techniques, and wet etching. The test device was then mounted in a tension-free plastic housing and was wire bonded to electrodes on a separately patterned ceramic substrate that connected the 18 modulator control lines (2 ground lines and 16 source lines) to external wires. Figure 2 is a photograph of a test device before wire bonding with an active aperture measuring 6.4 mm \times 3.8 mm. Each modulator has a dual-aperture configuration consisting of a central source electrode 160 μm wide surrounded by two 160- μm -wide ground electrodes (GND's) that provide electrical isolation between the modulators. The modulator grating period is $d = 400 \mu\text{m}$, and the interelectrode gaps (clear apertures) are $w = 40 \mu\text{m}$. Voltage applied to a specific modulator causes a symmetric index change in both apertures of that modulator. For normally incident He-Ne illumination ($\lambda = 633 \text{ nm}$) with polarization set perpendicular to the electrodes the measured $V_{2\pi}$ voltage of these modulators is 300 V.

A simple four-step scanning experiment was performed with the fabricated PAGES device illuminated by an expanded and collimated He-Ne laser beam. A Fourier-transform lens ($f = 375 \text{ mm}$) was placed behind the device to produce output spectra at the back focal plane of the lens. These spectra were directly imaged onto a CCD array. Figure ??? shows the output of the PAGES device for four different sets of applied voltages corresponding to four different linear phase slopes. The applied voltages were chosen to shift the output spectra laterally by fractions of $-1/4$, 0 , $+1/4$, and $+1/2$ of the fundamental frequency of the array ($1/d$). For the scanning

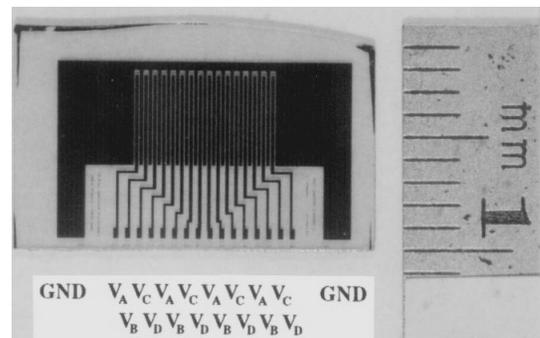


Fig. 2. Photograph of a PAGES device before mounting.

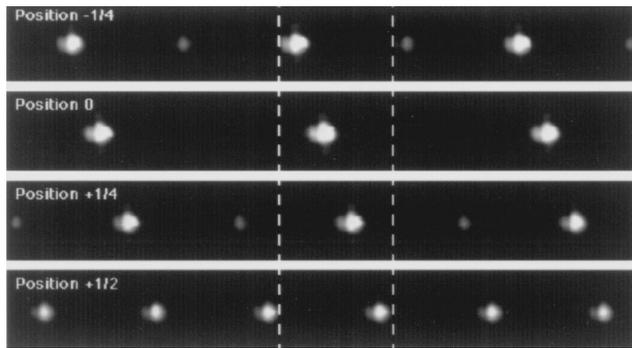


Fig. 3. Output of the PAGES scanner showing four programmed lateral shifts of the diffraction spectra.

experiment the control lines were tied together in sets of four, yielding four independent groups of modulators (see Fig. 2) supplied by a corresponding four-level voltage sequence $\{V_A, V_B, V_C, V_D\}$. To perform the four lateral shifts $-1/4$, 0 , $+1/4$, and $+1/2$ we applied control voltage sequences $\{V_{3\pi/2}, V_\pi, V_{\pi/2}, 0\}$, $\{0, 0, 0, 0\}$, $\{0, V_{\pi/2}, V_\pi, V_{3\pi/2}\}$, and $\{0, V_\pi, 0, V_\pi\}$, respectively, where $V_{3\pi/2} = 235$ V, $V_\pi = 155$ V, and $V_{\pi/2} = 95$ V. The primary, nonredundant scanning range of the central order is delineated in Fig. ??? by dashed lines. Position 0 (no applied voltage) shows the comb function of Eq. (3) centered on the optical axis. The other positions demonstrate the ability of the PAGES device to steer the 0th order of the comb array to either side of the optical axis with good contrast. The angular width (λ/d) of the central scanning zone is approximately 0.1 deg. The spot size of the comb orders in the output is determined by the aperture of the fabricated device. Also, because the phase modulators of the fabricated device are only partially filled (fill factor $w/d = 1/10$) the overriding sinc envelope of Eq. (3) is broadened by a factor d/w , allowing higher orders of the comb to pass into the output with relatively strong intensity. Note that an additional cosinusoidal envelope of the comb diffraction orders is also present because of the dual-aperture transmittance of the modulators, which causes strong modulation of alternating comb orders.

In future PAGES designs we will incorporate a cylindrical lenslet array on each side of the modulator array to increase the fill factor and thus concentrate most of the output energy into the shifted 0th comb order as given by Eq. (3). These lenslets will be aligned to illuminate only one slit from each modulator to avoid the cosinusoidal envelope. For the case of completely filled modulators the diffraction efficiency of the shifted 0th comb order can be written as⁸ $\eta_0(\Delta\varphi) = \text{sinc}^2(\Delta\varphi/2\pi)$, where $\Delta\varphi$ is the phase quantization error (see Fig. 1). This equation implies that high diffraction efficiencies ($>81\%$) of the primary 0th-

order output can be maintained if the stepped phase increments are restricted to $|\Delta\varphi| \leq \pi/2$. Fast switching responses ($0.5\text{--}50$ μs) are expected⁵ once proper high-speed voltage sources are packaged into the PAGES device. The scanner power requirements will be of the order of $(N/\tau)(CV_\pi^2/2)$, where C is the capacitance of a single modulator. Estimates place $C \approx 1$ nF for our current electrode design. Simulation and testing of alternative electrode designs are in progress to minimize both C (to ~ 1 pF) and V_π (to ~ 50 V) to achieve reasonable power requirements for a large scanner array. A multistage scanner architecture is also being investigated to permit a large number of output points N to be addressed with a minimum number of control lines. Our goal is to build a PAGES device with 1024 resolvable spots and a switching time of 1 μs , which will yield combined space-time bandwidths of 10^9 points/s. The extension to two-dimensional scanning follows directly by crossing a pair of one-dimensional PAGES devices.

In conclusion, we have introduced, designed, and fabricated a novel programmable diffractive optical element, using a 16 channel array of partially filled phase modulators in PLZT. By varying the control voltages supplied to the array, we have demonstrated selective beam steering to four distinct positions in the scanning range. Further research is proceeding to reduce the required control voltages, to maximize the central beam diffraction efficiency, and to increase the number of resolvable spots. Time response analysis will also be performed. The PAGES device concept is an inherently light-efficient means for wave-front control and has potential appeal for numerous applications including optical scanning, programmable interconnects, routing, and dynamic focusing elements.

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