Progress in transparent, flat-panel holographic displays enabled by guided-wave acousto-optics

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ABSTRACT

We have previously introduced a monolithic, integrated optical platform for transparent, flat-panel holographic displays suitable for near-to-eye displays in augmented reality systems. This platform employs a guided-wave acousto-optic spatial light modulator implemented in lithium niobate in conjunction with an integrated Bragg-regime reflection volume hologram. In this paper, we depict analysis of key system attributes that inform and influence the display system performance, including the use of strobed illumination to enforce acousto-optic grating stationarity and the influence of the acousto-optically driven spatial Nyquist rate.

Keywords: holography, near-to-eye display, waveguide optics

1. INTRODUCTION

We have previously introduced an architecture for transparent, flat-panel electrophoretic display suitable for near-to-eye augmented reality applications.\textsuperscript{1} In contrast to other architectures for near-to-eye holographic display involving the use of pixelated microdisplays,\textsuperscript{3–7} our solution requires no supporting optics or discrete microdisplays to deliver a holographic image to the viewer. Structurally, our solution is comprised of a guided-wave acousto-optic modulator implemented in anisotropic lithium niobate with an integrated Bragg reflection grating as shown in Fig. 1. Because the guided-wave device inherently operates diffractively only in a single dimension and over a limited acousto-optic interaction length, the display is horizontal-parallax only – increased horizontal view extent is achieved by spatially multiplexing several transducers (i.e., multiple holographic elements, or hogels) per waveguide and vertical resolution is achieved by employing multiple, vertically stacked waveguide channels (as depicted in Fig. 2). A fabrication methodology for this entire integrated optic device based around femtosecond laser micromachining has been previously presented.\textsuperscript{2}

We have previously depicted a drive scheme for operating such a multi-hogel, multi-channel flat-panel holographic display via time-division multiplexing and beam strobing. In this paper, we present an analysis of this drive scheme to provide intuition as to achievable resolution, expressible depth, and overall expected image quality. We furthermore present an analysis of expected addressable angular volumes and depict progress in fabrication of display elements via femtosecond laser micromachining.

2. STROBED ILLUMINATION, RF NYQUIST RATE, AND SYSTEM RESOLUTION

Due to the non-stationarity of traveling acoustic modulation signals, holographic display architectures based around acoustic-optic modulators have historically employed temporally-modulated de-scanning elements, such as polygonal mirrors, to produce stationary image outputs for the viewer. In order to eliminate the need for discrete de-scanning elements, our display architecture employs strobed illumination to enforce some degree of image stationarity in the display output. Such operation has been presented as a solution to overcoming non-stationarity when acousto-optic modulators have been used in beam shaping applications.\textsuperscript{9} As shown in an earlier publication,\textsuperscript{1} an example timing diagram for strobed operation of the proposed device is depicted in Fig. 3. $\tau_{\text{fill}}$ is the time duration over which the aperture is filled by the acoustic pixel stream and $\tau_{\text{pixel}}$ is the time duration over which a single pixel is acoustically drawn. The duty cycle is then

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Figure 1. $x-y$ cross-section (side view) of proposed guided optical wave SAW device with integrated Bragg gratings.

Figure 2. $z-y$ cross-section (top view) of multi-element, multi-channel SAW device.

Figure 3. Timing diagram for pulsed laser illumination of SAW devices.
\[ D = \tau_{\text{pixel}}/\tau_{\text{fill}}. \]  
\[ \tau_{\text{fill}} \]  
can be found as \( \tau_{\text{fill}} = l/v \), where \( l \) is the interaction length and \( v \) is the velocity of the propagating surface acoustic wave. For \( x \)-cut LiNbO\(_3\), \( v = 3909 \text{ m/s} \); assuming an interaction length \( l = 1 \text{ cm} \), \( \tau_{\text{fill}} = 2.558 \text{ \mu s} \). For a 400 Mpixel/s pixel clock from a modern graphics processing unit, \( \tau_{\text{pixel}} = 1/400 \text{ Hz} = 2.5 \text{ ns} \). Note that each illumination pulse is tied to the time taken for the graphics processing unit to output one filled aperture’s worth of pixels.

Given a pixel time \( \tau_{\text{pixel}} = 2.5 \text{ ns} \), the effective spatial pitch of an acousto-optically induced pixel is \( p = v \times \tau_{\text{pixel}} = 3909 \text{ m/s} \times 2.5 \text{ ns} = 9.77 \text{ \mu m} \). Note that this value influences the number of effective acoustic pixels that fit within the interaction length of a single transducer and therefore imposes a bound on the best possible resolution (system MTF) achievable as well as imposing a bound on achievable angular sweep on a per-hogel basis; it should be noted that the pixel clock of the driving signal (i.e., the RF Nyquist rate) dictates the cutoff spatial frequency. The pulse duration and timing has also influence over the effective display resolution (i.e., perceptible image blur). As pulses are triggered when the acoustic aperture has been fully filled, the effective perceived intensity results from the eye’s integration of all diffracted Fresnel field intensities over the time window of the illumination pulse (as depicted in Fig. 4). More precisely, the perceived intensity pattern as integrated by the eye resulting from illumination of a traveling acoustic signal with an illumination pulse of finite duration can be expressed via the superposition of Fresnel-diffracted intensities as

\[ I(x) = \int_{-\tau/2}^{\tau/2} \left| \int_{-\infty}^{\infty} f(v \ast t) e^{j \frac{2\pi}{\lambda z} z' x'} e^{-\frac{j\pi}{\lambda z} z x} dx' \right|^2 dt \]

where \( I(x) \) is the perceived one-dimensional intensity, \( t \) is time with \( t = 0 \) dictating the time that the aperture has been fully filled, \( \tau \) is the pulse duration, \( v \) is the acoustic propagation velocity, \( f(x) \) is the spatial (temporally-variant) acousto-optic modulation signal, \( z \) is the observation distance, and \( \lambda \) is the illumination wavelength.

\[ \text{Figure 4. Kernel blur when illuminating a traveling acousto-optic chirped grating with a pulse of finite duration.} \]

In addition to bounds on system resolution due to the RF Nyquist rate of the driving signal, the limited interaction length available for the coherent aperture, and the non-infinitesimal pulse duration of the illumination, our display architecture is also limited in achievable resolutions as a function of the depth at which a scene point is reconstructed by the display. Effective PSF “broadening” occurs as the depths at which points are reconstructed increases relative to the hologram plane; this phenomenon is depicted in Fig. 6, in which the PSF is “baseline-limited” due to the RF Nyquist rate of the driving source for points close to the hologram plane, then broadens as the chirped lenslets required for progressively deeper points begin to “overfill” the available spatial aperture and are low-pass filtered.
Figure 5. Full-width at half-maximum of the intensity point-spread function of a diffractive chirp lenslet as a function of maximal pixel clock.

Figure 6. Full-width at half-maximum of the intensity point-spread function of a diffractive chirp lenslet as a function of chirp focal length.
Figure 7. Full-width at half-maximum of the perceived intensity spread function of an acousto-optically driven diffractive chirp lenslet with focal length 1 cm as a function of pulse illumination duration, for a drive signal with pixel clock 400 Mpixel/s (pixel time 2.5 ns). Note that this function represents the temporal integral taken by the viewer’s eye in Eq. 1.

Figure 8. Full-width at half-maximum of the perceived intensity spread function of an acousto-optically driven diffractive chirp lenslet as a joint function of chirp focal length and pulse illumination duration, for a drive signal with pixel clock 400 Mpixel/s (pixel time 2.5 ns). Note that this function represents the temporal integral taken by the viewer’s eye in Eq. 1.
To provide intuition for display performance, we numerically consider diffraction from an acousto-optically driven chirp signal in Figs. 5-8. Fig. 5 depicts the effect of an increased RF Nyquist rate on achievable display resolutions. Fig. 6 depicts increasing broadening of the diffractively-generated point-spread function with increasing point depth due to the limited 5mm interaction length of the device. Fig. 7 depicts the increasing broadening of the effective intensity spread perceived by the eye over its integration time as a function of illumination pulse duration for an acoustically-traveling diffractive chirp lenslet in LiNbO$_3$. Fig. 8 depicts the effective intensity spread perceived by the eye over its integration time as a joint function of illumination pulse duration and point depth. It should be noted that the best achievable resolutions are jointly provided for short illumination pulses, scene points close to the hologram plane, and high RF pixel clock rates. The choice of display parameters is likely to be scene- and application-dependent, and should be informed by constraints on required resolution for particular depth ranges, light throughput, and tolerable fidelity.

3. PROJECT STATUS - FABRICATED WAVEGUIDES AND GRATINGS

At the time of this writing, we have successfully fabricated volume phase gratings in lithium niobate via femtosecond laser micromachining that exhibit multilayer diffractive properties (see Fig. 9). We have furthermore identified a solution for fabricating high-contrast waveguides based around proton-exchange and femtosecond laser micromachining (see Fig. 10). Experimental results depicting the performance of functional holographic elements of the type depicted in Fig. 1 and scaled displays of the type depicted in Fig. 2 will be presented in future publications.
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