Experimental characterization of leaky-mode spatial light modulators fabricated via direct laser writing

Sundeep Jolly[a], Bianca Datta[a], Vik Parthiban[a], Daniel Smalley[b], and V. Michael Bove, Jr.[a]

[a]Media Laboratory, Massachusetts Institute of Technology, 75 Amherst St., Cambridge, MA 02142, United States
[b]Department of Electrical and Computer Engineering, Brigham Young University, 459 Clyde Building, Provo, UT, United States

ABSTRACT

We have previously presented a novel spatial light modulator appropriate for use in transparent, flat-panel holographic display applications. Our architecture consists of an anisotropic leaky-mode coupler and integrated Bragg reflection grating as a monolithic device implemented in lithium niobate and is fabricated using direct femtosecond laser writing techniques. In this paper, we present a methodology for the experimental characterization of holographically-reconstructed point spread functions from sample devices.

Keywords: femtosecond laser micromachining, holographic display, lithium niobate, surface acoustic waves, guided-wave acousto-optics

1. INTRODUCTION

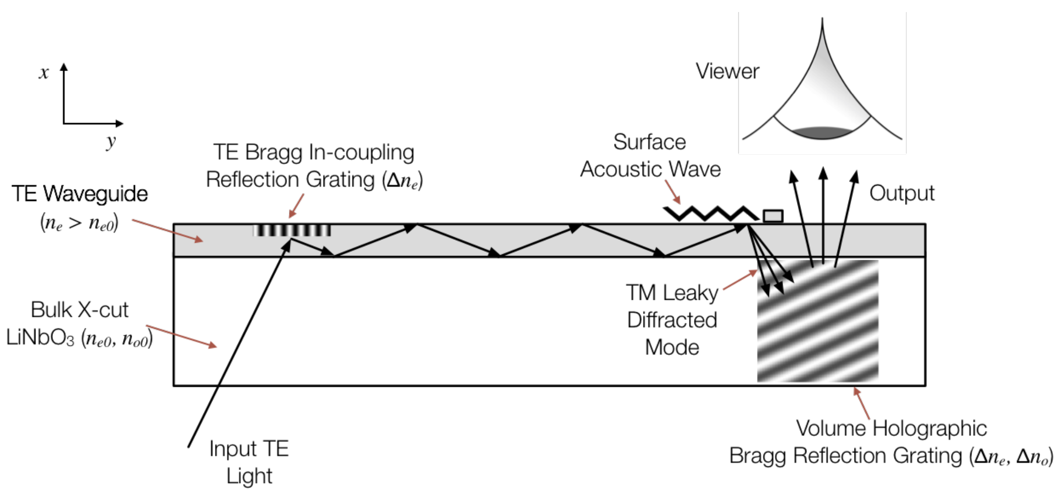

Figure 1. Fully monolithic guided-wave acousto-optic device implemented in x-cut $LiNbO_3$ and encompassing an anisotropic waveguide, surface acoustic wave transducer, and volume reflection Bragg grating.

We have previously introduced a monolithic platform for transparent, flat-panel holographic displays based around guided-wave acousto-optic spatial light modulation in lithium niobate[1] based around our earlier edge-operating integrated optic spatial light modulators.[2] As shown in Fig. 1, this platform is based around an anisotropic waveguide patterned on the surface of an x-cut $LiNbO_3$ substrate that guides light of TE polarization (relative to the plane of incidence dictated by the $LiNbO_3$ crystal axis and the y-direction of propagation). As a guided-wave acousto-optic device, RF excitations of a surface acoustic wave transducer patterned on one end of the waveguide act to induce a traveling Rayleigh mode of mechanical perturbation along the waveguide crystal axis. The SAW induces mechanical strain and thereby locally perturbs the anisotropic permittivity tensor. Because of crystalline asymmetry, guided-mode light that interacts with the traveling SAW is modulated in phase relative to the information encoded by the RF excitation signal and is furthermore rotated in polarization in a TE-to-TM mode conversion and thereby leaks out of the waveguide into a leaky mode. For transparent, flat-panel holographic displays, the leaky-mode light is incident on a reflection-mode volume Bragg grating that acts to redirect the light back through the waveguide layer to a viewer.

We have also previously presented a fabrication methodology for such monolithic devices based around femtosecond laser micromachining and imaging performance analysis for such devices.[3,4] In this paper, we depict current progress in the femtosecond-laser-based fabrication of metal transducers and volume reflection Bragg gratings and further present a methodology for the experimental characterization of holographically-reconstructed point-spread functions reconstructed from said devices.

2. PROGRESS IN FEMTOSECOND LASER MICROMACHINING AND FABRICATED STRUCTURES

While integrated optic devices have traditionally been fabricated using standard lithographic processes, our chosen fabrication modality for prototyping display elements is based around femtosecond laser micromachining and comprises the fabrication of waveguide masks and aluminum transducers via laser ablation of a thin metal layer and volumetric integration of refractive index features[5] needed to form volume gratings. Such an approach offers flexibility in the choice of design parameters and affordances in exploring a range of parameters for fabrication without the need to replace tooling or employ a complex multi-step lithographic process for rapid prototyping.

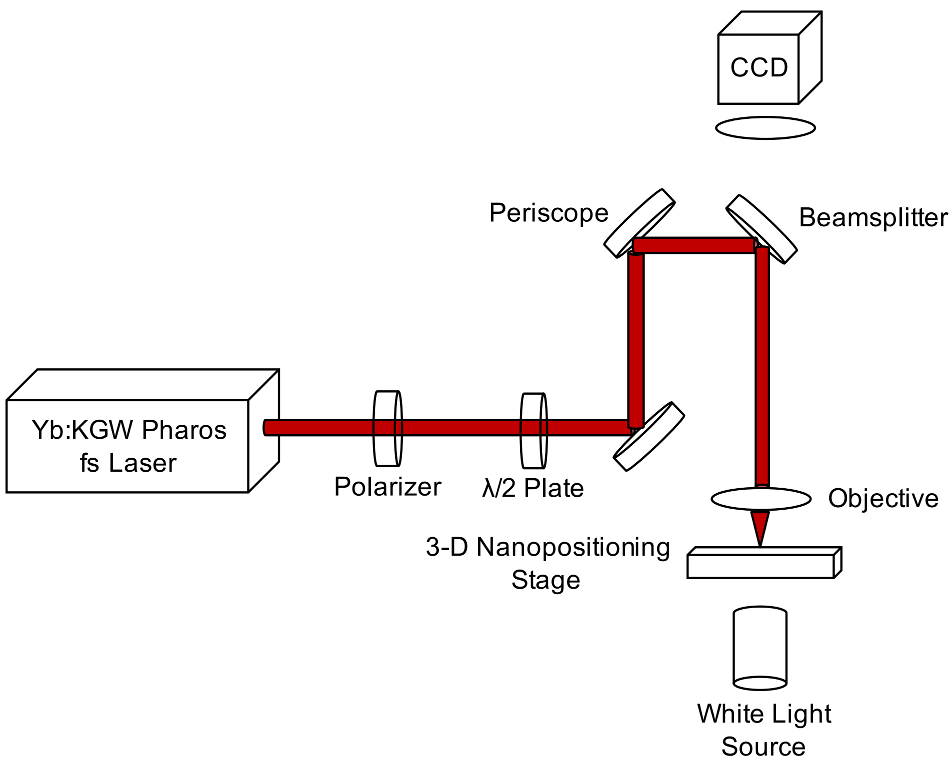

Figure 2. Setup for femtosecond laser micromachining.

Fig. 2 depicts the optical schematic of our implemented system for femtosecond laser processing. Femtosecond laser pulses from a Yb:KGW mode-locked laser (PHAROS 15W, Light Conversion, Ltd.) are focused through a high-resolution microscope objective onto the surface or volume of a medium to be ablated or densified. For a detailed description of the workings of this system or of sample mechanisms related to material perturbation, please refer to our earlier work.[3,4]

2.1 Volume Bragg Grating Fabrication

Volumetric integration of refractive index features is achieved via laser modification within the crystalline volume. A depiction of design considerations and preliminary results is depicted in our earlier work.[6] In this section, we present progress in the fabrication of volume Bragg gratings via femtosecond laser micromachining.

For the current experiments, we operate the fs laser at the operating wavelength $\lambda = 515$ nm, with a pulse repetition rate of 100 kHz, a pulse energy of 2 μJ (average laser power $P = 200$ mW), and a stage translation velocity of 5 mm/s. For finely pitched gratings (e.g., $\Lambda < 5$ μm), a high-resolution NA=0.7 microscope objective is used. For volume Bragg gratings, grating layers are spaced in depth by 2.5 μm, and gratings are fabricated 100 μm below the $LiNbO_3$ surface.

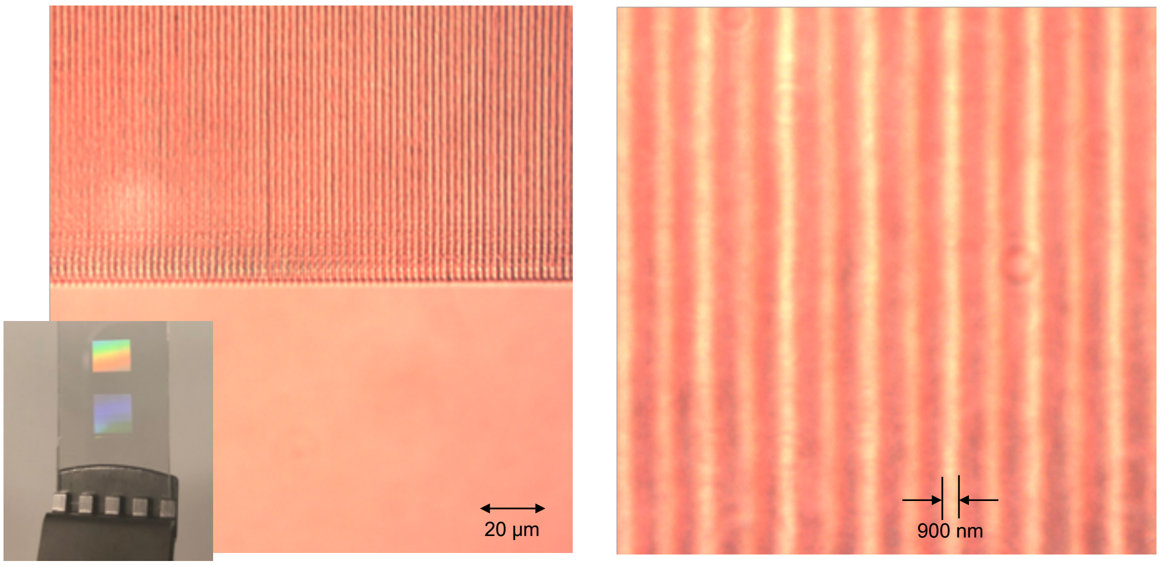

Figure 3. Fabricated volume Bragg gratings with $\Lambda = 2$ μm, $N = 20$ layers, and layer spacing 2.5 μm.

Fig. 3 depicts fabricated volume Bragg gratings, with $\Lambda = 2$ μm. These gratings are comprised of 20 layers, written in a bottom-to-top fashion, with a nominal "line" feature dimension < 1 μm (dictated by the nominal diffraction-limited spot size indicated by the numerical aperture of the writing objective).

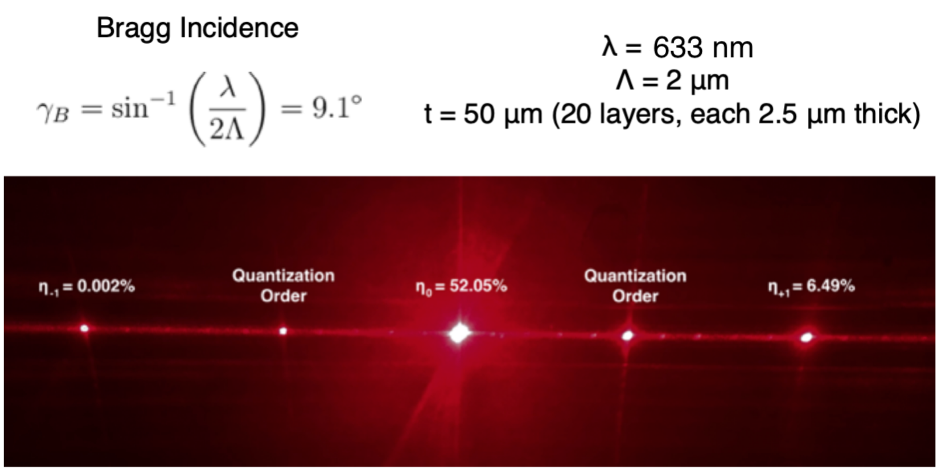

Figure 4. Bragg grating characterization with laser beam incident at Bragg angle and resulting asymmetric diffraction profile, depicting very strong energy transfer into the +1st diffracted order at the expense of energy transferred into other orders.

Fig. 4 depicts characterization of the fabricated Bragg gratings, showing asymmetric effects in volume diffraction when a laser beam at $\lambda = 633$ nm is incident upon the grating at the Bragg angle $\gamma_B = \sin^{-1}\left(\frac{\lambda}{2\Lambda}\right) = 9.1°$. Note that the diffraction pattern observed is strongly asymmetric at Bragg incidence for the input beam direction, consistent with a thick grating exhibiting diffraction in the Bragg regime.

2.2 Transducer Fabrication via Ablation

We have previously depicted a femtosecond-laser-based fabrication methodology for surface acoustic wave transducers based around laser-induced forward-transfer.[7] Because of issues related to transducer morphology, roughness, and metal-substrate adhesion, we have additionally examined laser ablation of aluminum as an alternative for the fabrication of surface acoustic wave transducers. Such a technique has also been previously explored by Gertus *et. al.*,[8] with success in trial RF electrical tests.

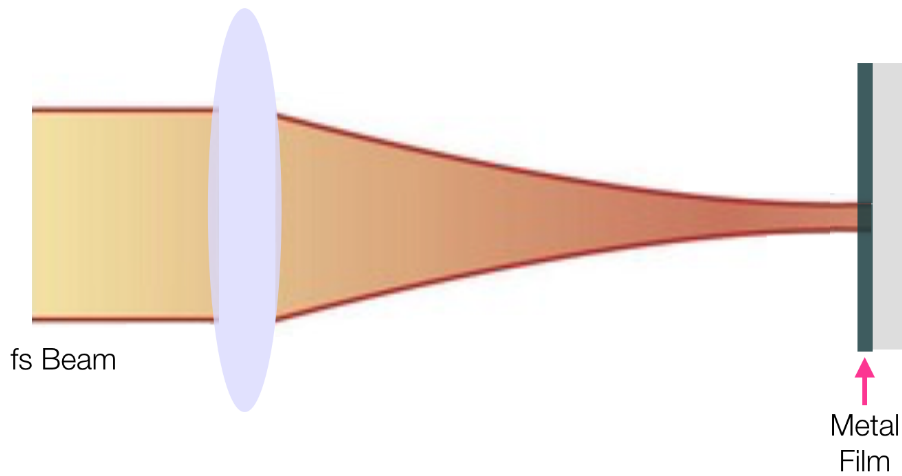

Figure 5. Process for femtosecond laser ablation of aluminum.

Fig. 5 depicts a process for femtosecond laser ablation of aluminum for the fabrication of surface acoustic wave transducers. Here, a femtosecond laser beam is focused through an objective onto a deposited thin film of aluminum on a carrier substrate of $LiNbO_3$. The metal in the region of sufficient femtosecond pulse energy density in the vicinity of the nominal beam focus position is ablated off the carrier substrate, and thereby, raster writing an "inverse" pattern relative to the desired remaining metal pattern will leave only the desired pattern while preserving the original thin film's morphology, thickness, and adhesion to the substrate. In our trials, we employ a 200 nm thick layer of aluminum, deposited on the $LiNbO_3$ substrate by electron-beam evaporation. A pulse energy in excess of 1.5 μJ using an NA=0.28 microscope objective with a stage translation velocity of 1 mm/s is sufficient to ablate aluminum in this configuration.

Fig. 6 depicts a fabricated transducer using this methodology. Here, the transducer period is $\Lambda = 25\mu$m. Note that, in contrast to using LIFT-based methods, this transducer has excellent surface morphology and retains good adhesion to the carrier substrate.

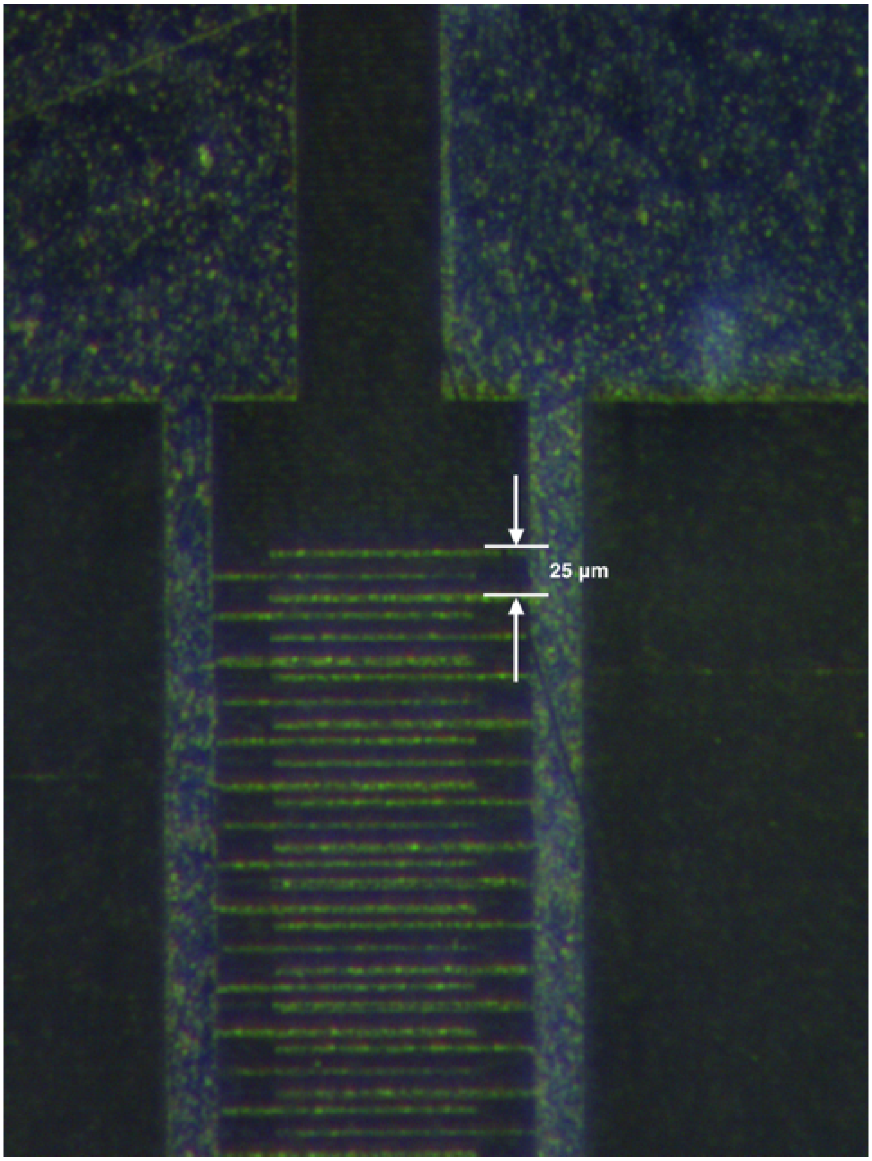

Figure 6. Fabricated transducer via femtosecond laser ablation of aluminum.

3. CHIRP CHARACTERIZATION

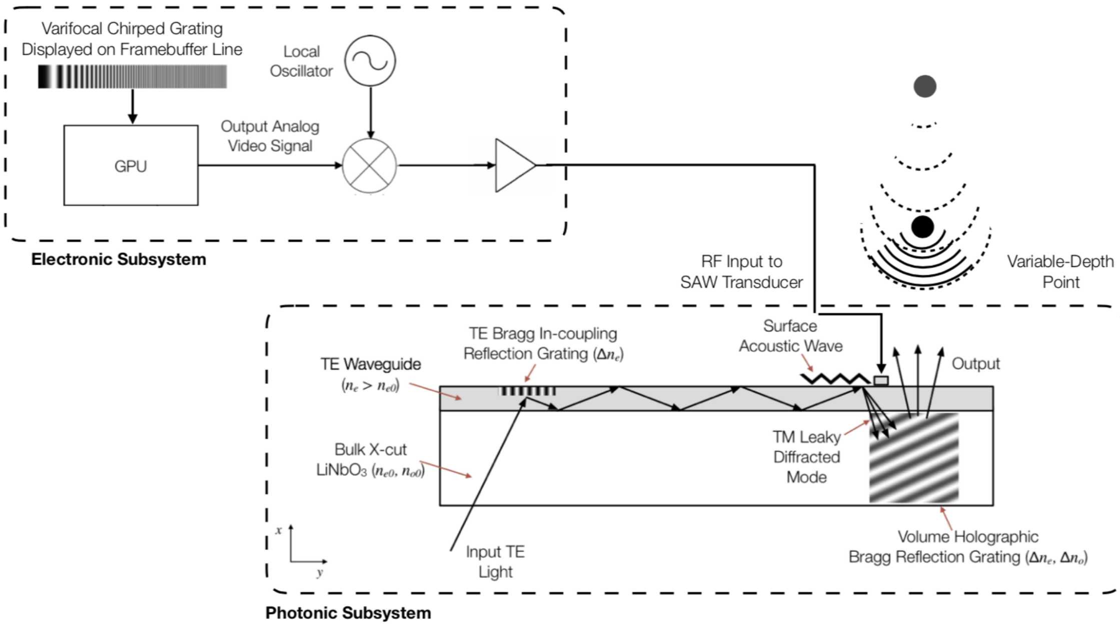

Figure 7. Methodology for characterizing point spread functions from device elements.

We have previously presented analytical results depicting the influence of system parameters on display imaging performance.[9] Fig. 7 depicts a methodology for experimental characterization of holographically-reconstructed point spread functions from sample devices. Electrically, chirped diffraction gratings are displayed on a GPU's framebuffer line. These chirps are appropriately space-limited and band-limited to account for the measured (or expected) device interaction length and temporal bandwidth as dictated by its acousto-optic transfer function, respectively, while also being appropriately up-converted (whether in software or the RF electrical domain) to match the center frequency of the device passband. The analog output from the GPU video channel is possibly upconverted (if the device passband falls beyond the limits of the analog bandwidth dictated by the GPU clock, typically 200 MHz), then amplified and filtered through an impedance-matching network, before finally exciting the transducer and inducing a propagating surface acoustic wave containing the chirped-grating information.

Optically, pulsed TE mode light is coupled into the waveguide before being modulated by the acoustic chirped grating. The light is pulsed when the serial stream of RF samples corresponding to a single chirped grating completes, typically as indicated via the GPU's horizontal sync pulses. The pulse duration is typically on the order of several tens of nanoseconds, while the time between adjacent pulses is typically on the order of several microseconds. Note that we have defined illumination parameters in a previous publication.[9]

The use of acoustic chirped gratings in this fashion allows for the creation of both real and virtual image points, and for the characterization of point spread functions corresponding to different lateral and depth-wise point positions.

4. FUTURE WORK AND CONCLUSIONS

In this paper, we have presented recent results on laser-based fabrication modalities for integrated optic components and an experimental methodology for the characterization of $LiNbO_3$-based leaky-mode spatial light modulators appropriate for use in future fully-monolithic, transparent, and flat-panel holographic video displays. Results of said characterization and sample test imagery resulting from the scale-up of multiple devices operating in serial and parallel will be presented in subsequent publications.

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