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Angular and spatial light modulation by single digital micromirror device for display applications

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ABSTRACT

A single Digital Micromirror Device with a single illumination source projects multiple, independent patterns into corresponding directions across a nearly-doubled angular extent by time multiplexing and by nanosecond illumination pulse synchronization for a binary patterned programmable blazed grating. The resulting "Angular Spatial Light Modulator" (ASLM) system nearly-doubles the étendue of a DMD-type SLM and creates a multiplication factor for the output pixel count and effective pixel density. We demonstrate an extended FOV display, a light-field projector, and a multi-view display which can be implemented into AR/VR systems. We present an implementation update using the DLP7000 DMD, increasing output pixel count by and effective pixel density orders-of-magnitude beyond traditional SLM systems while achieving an extended field-of-view and/or eye-box size due to the increased étendue.

Keywords: DMD, ASLM, display, AR, VR, micromirror, beam steering, pattern steering

1. INTRODUCTION

Multi-perspective displays with high spatial resolution and high angular resolution displays are highly desirable[1,2]. Increases in spatial resolution and inter-perspective angular resolution are often both dependent on physical pixel count and physical pixel pitch of a spatial light modulator (SLM), as seen in integral imaging displays[3]. However, this causes direct tradeoffs between spatial resolution and number of perspectives. Scanning mechanisms have been implemented with SLMs to create additional time-multiplexed effective pixels at cost to system complexity[4,5].

We previously reported on a programmable blazed grating beam steering technique by Digital Micromirror Device (DMD)[6]. We then reported on the "Angular Spatial Light Modulator," a system merging DMD-based beam steering and pattern creation for a single-plane pattern creation and steering[7].

Section 2 reviews the DMD-based beam steering technique. Section 3 reviews the ASLM pattern steering technique. Section 4 presents our DLP7000 update for increased spatial resolution, angular pattern steering resolution, and speed.

2. DMD BEAM STEERING REVIEW

2.1 Programmable blazed grating by DMD

The DMD has an array of micromirrors which each rotate between +12° and -12° binary states. The micromirrors form a blazed grating with +12° and -12° binary programmable blaze angles. Illuminating the DMD with a short pulse (8 ns) during the microsecond transition of the micromirrors effectively freezes the micromirrors an any angle between the between +12° and -12° binary states, enabling fully continuous control of the blaze angle[6]. Figure 1 depicts a simulated phase map across the DMD[6].

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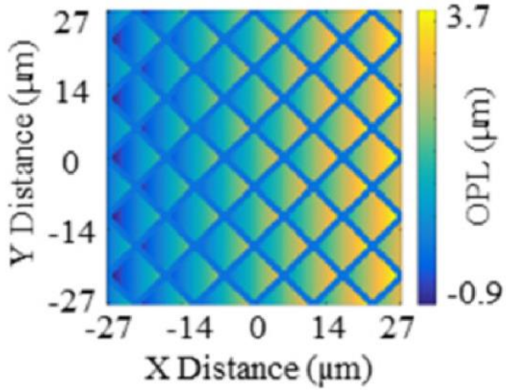

Figure 1. Phase map of a 5×5 array of 10.8 µm corner-to-corner pitch micromirrors with 3° angle-of-incidence illumination. The micromirrors shown are fixed at -12° relative to the DMD structure surface. Reprinted[6].

The beam steering technique actuates all micromirrors for a periodic phase map. The DLP3000, with a 10.8 µm corner-to-corner pixel pitch, can steer across 5 output diffraction orders at 905 nm. Figure 2 shows the 5 discrete output beam steering directions[6].

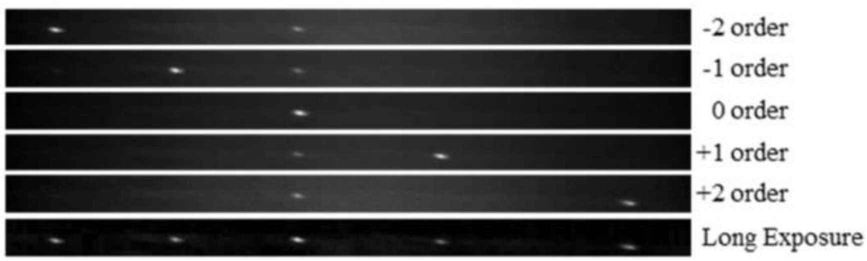

Figure 2. Discrete steering points across five output diffraction order directions. The 0^{th} order diffraction order includes the cover glass reflection which is visible when steering the beam in any diffraction order. Reprinted[6].

2.2 Single-chip lidar application

The 5 discrete beam steering directions were implemented into a lidar system[6]. The DLP3000 LightCrafter has a 4 kHz binary pattern reset rate. The lidar system achieved 3.34 kHz sampling due to processing time for the driving Arduino Uno microcontroller and time-to-digital converter. Figure 3 shows a capture from the lidar system[6].

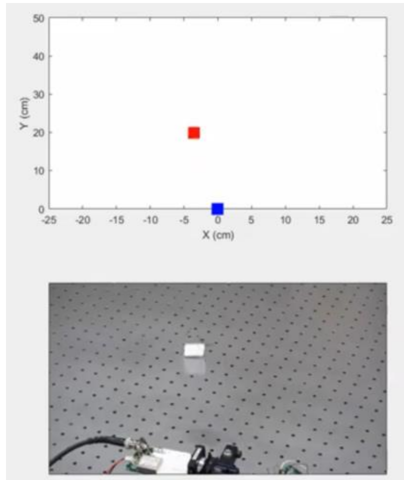

Figure 3. Lidar capture (top) and experimental setup with target (bottom). Reprinted[6].

3. ASLM PATTERN STEERING REVIEW

The ASLM pattern steering technique also illuminates the DMD during the micromirror transition. Rather than actuating all micromirrors across the array, the ASLM technique only actuates preprogrammed micromirrors to create a binary amplitude spatial pattern. The transitioning micromirrors collectively create a beam steering phase map to direct the light into a particular output diffraction order[7].

Creating an arbitrary pattern to direct into one of the discrete output diffraction orders requires that all micromirrors start in the same position. Figure 4 shows the required sequence to steer programmable patterns into programmable directions.

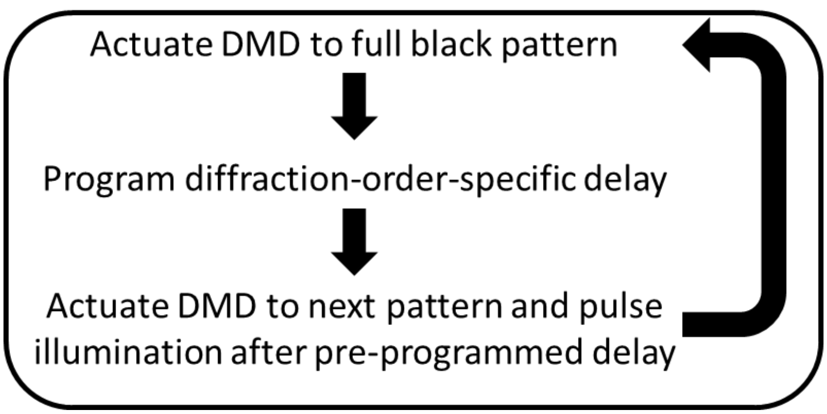

Figure 4. ASLM pattern steering sequence.

An ASLM extended display projected each diffraction order through a microlens onto the same observation screen. Figure 5 shows (a) a schematic depiction and (b) the experimental result[7].

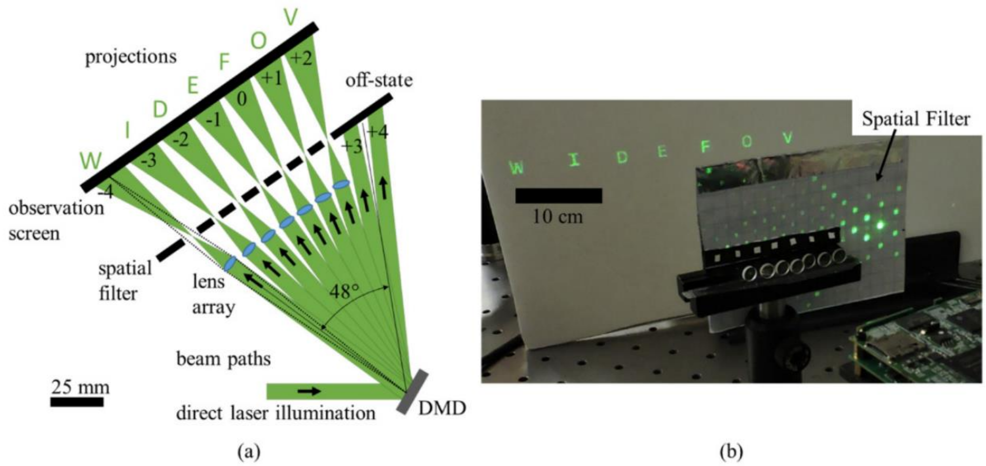

Figure 5. ASLM extended display including (a) schematic depiction and (b) experimental result. Reprinted[7].

Light field, multi-view, and direct-view displays were also experimentally demonstrated[7]. Multiple sources were implemented to add a second axis of steering[7]. Figure 6 shows 2D pattern steering.

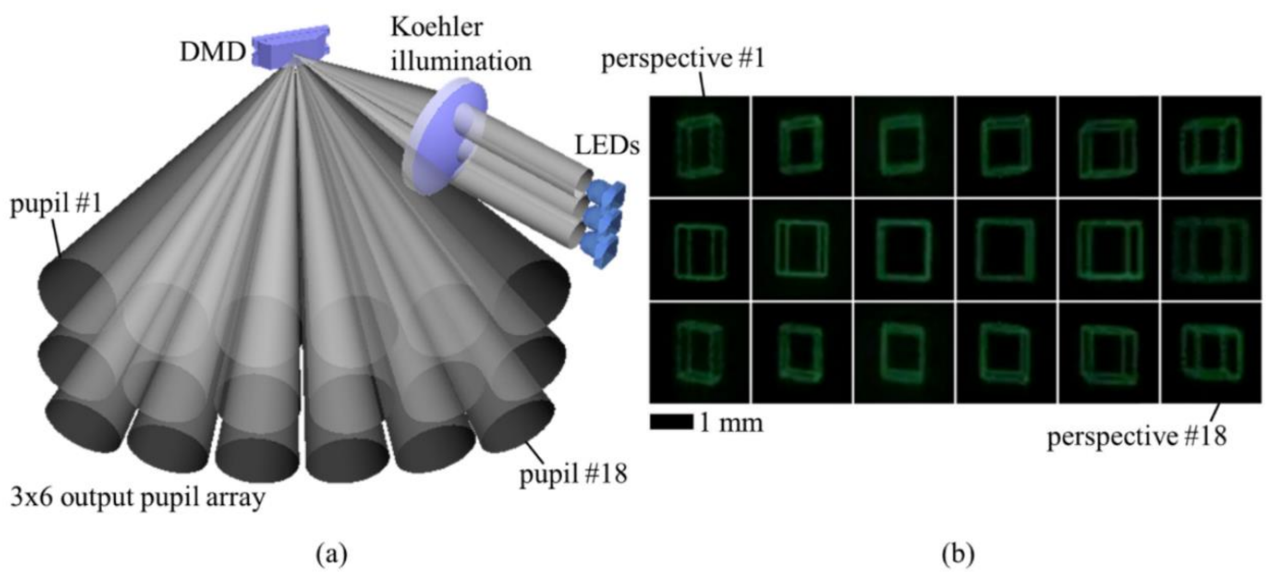

Figure 6. 2D pattern steering including (a) schematic depiction and (b) captured images of the 6×3 array perspectives. Reprinted[7].

We previously commented on the scalability of the DMD-based ASLM technique[7]. There is significant scaling potential given the highly developed DMD technology, all previously based around binary states. From a demonstration perspective, the DLP7000 or DLP9500 offer significant advantages, including larger micromirror counts, greater pixel sizes for more diffraction orders, and significantly faster reset rates.

4. DLP7000 UPDATE

Similar to the DLP3000 implementation shown in Fig. 5, we implemented pattern steering using a DLP7000. Figure 7 shows the observation screen result with corresponding output diffraction order numbers.

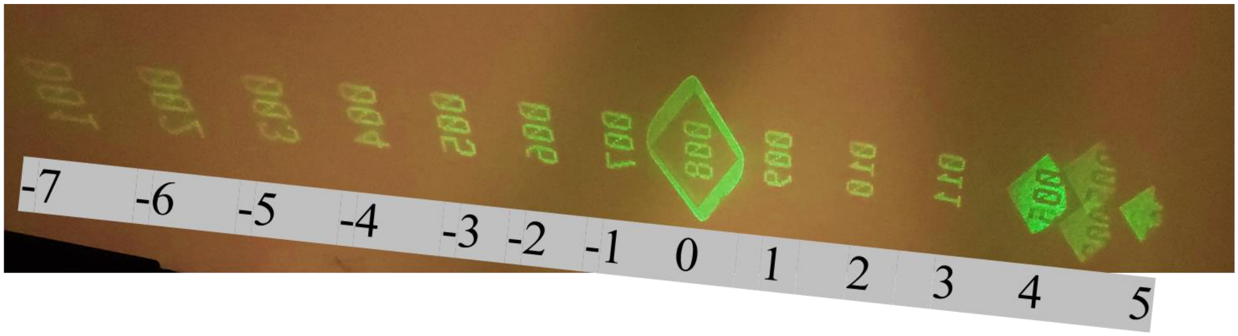

Figure 7. Observation screen of ASLM output by a DLP7000 DMD using all output diffraction orders across the +12° and -12° micromirror span. The projected patterns have reversed parity.

Eleven (11) non-off-state diffraction orders were able to be used to project arbitrary patterns: -7 to 3. The 0^{th} diffraction order is boarded by reflection from the surrounding DMD structure. Diffraction orders 4 and 5 are non-usable off-state diffraction orders: light from off-state (non-transitioning) micromirrors are emitted in this direction. Off-state light covers two diffraction orders for two reasons. First, the output diffraction order directions are determined by the angle-of-incidence and micromirror array structure and not the micromirror angular throw[6,7]—essentially, the landed off-state micromirrors will not direct light into one diffraction order by default. Second, voltage fluctuations occur for the landed off-state micromirrors causing slight rotation, spreading light across the two diffraction orders depending on when pulse illumination occurs. The 11 patterns span 44°

Direct view of the DLP7000 from the direction of an output diffraction order corrects the parity reversal, as anticipated. Figure 8 shows the DLP7000 viewed from the -5 diffraction order displaying "003".

Figure 8. Direct viewing of the DLP7000. Oversaturation of the photo reduced image quality significantly, but full DLP7000 resolution is available.

5. CONCLUSION

We have overviewed the DMD-based programmable blazed grating beam steering technique by pulse-pulse laser illumination of transitioning micromirrors. The technique was demonstrated an a single-chip lidar implementation. We also overviewed the implementation of the DMD-based beam steering technique with simultaneous spatial modulation across the micromirror array for Angular Spatial Light Modulation (ASLM). The ASLM technique was implemented for an extended display and 2D pattern steering light field display. We presented an update of a DLP7000 implementation outputting 11 independent and programmable patterns across 44°. The DMD-based ASLM technique allows time, space, and angle multiplexed modulation modalities at a single plane for a significant advancement in display systems.

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