PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

# Stability of diffractive beam steering by a digital micromirror device

Guan, Jiafan, Evans, Erik, Choi, Heejoo, Takashima, Yuzuru

Jiafan Guan, Erik Evans, Heejoo Choi, Yuzuru Takashima, "Stability of diffractive beam steering by a digital micromirror device," Proc. SPIE 11698, Emerging Digital Micromirror Device Based Systems and Applications XIII, 116980I (5 March 2021); doi: 10.1117/12.2582899

SPIE.

Event: SPIE OPTO, 2021, Online Only

# Stability of diffractive beam steering by a Digital Micromirror Device

Jiafan Guan*[a], Eric Evans[a], Heejoo Choi[a], and Yuzuru Takashima[a]

[a]College of Optical Sciences, University of Arizona, 1630 E. University Blvd., Tucson, AZ, USA, 85721

## ABSTRACT

Diffractive beam steering by Digital Micromirror Device enables an efficient way to simultaneously manipulate light both in the spatial and angular domain by spatial and time multiplexing while keeping large area and angular throw product. Long-term stability and susceptibility of beam and image steering rely on how synchronization of ns laser pulse and transition of micromirrors is maintained over time and through variation of device temperature. The long-term performance of the beam steering is evaluated by monitoring diffraction efficiency over 350 hrs. with a 360 Hz repetition rate. Also, diffraction efficiency was monitored while increasing the temperature of the mirror array from 45 to 75 degrees C. Over the period, stable beam steering was observed. A decrease in diffraction efficiency under high temperature was observed. We confirmed readjusting synchronization timing recovered the diffraction efficiency to the level of room temperature. The experimental results show a stable operation of diffractive beam steering by DMD is feasible for the long term, and even under variation of temperature by adaptively adjusting synchronization timing of laser pulse to starting timing of DMD mirror transition.

**Keywords:** Beam steering, stability, digital micromirror device, synchronization, heat cycling

## 1. INTRODUCTION

Laser beam steering technology has been actively researched for light detection and ranging (lidar) systems and advanced display system in recent years [1]. Recently using a Digital micromirror device (DMD) for diffractive beam and image steering has been proposed. The operation principle relies on synchronizing micro mirrors' movement with short nanosecond illumination that effectively "freeze" micromirror' s movement. The method also enables simultaneous modulation of amplitude and phase that opens up with various applications of DMD beyond the state of the art [3,4].

Conventionally, DMD has been used as a binary spatial light modulator where each of pixels, a micrometer size reflective mirror, tilts in +/- 12 degrees. The incident light is spatially modulated by the tilted mirror. Beam steering in this spatial light modulation mode is feasible, for example by displaying computer generated hologram (CGH) pattern on DMD. Alternatively DMD at the back focal plane of lens works as a beam steerer by selectively turning on pixels. However, those methods suffer from low photon throughput. Diffraction efficiency of binary amplitude hologram is about 10%. In lens-based beam steering, only portion of DMD pixels reflects light to lens. In contrast, the DMD-based diffractive beam steering works as a programmable blazed grating which has an inherently high diffraction efficiency, close to 100% in theory. In addition, angular throw of beam covers +/- 24° while keeping beam size as large as DMD mirror array area, for example 140mm$^2$ with high end DMD device [2], therefore, etendu (or Lagrange Invariant) of the lidar is kept high. A high scan rate, i.e. over 20 kHz is feasible while minimizing the number of moving parts. [3,4].

The diffractive DMD-based beam steering relies on a precise synchronization of the illumination pulse to micro mirrors' transitional state which is typically couple of micro seconds [5, 6]. Highly reliable and stable operation of DMD in the spatial light modulation mode was reported as well as is proven as various products [7, 8]. For the purpose of stable beam steering operation utilizing dynamic mirror transitional sate, a long terms stability as well as sensitivity of the synchronization timing with respect to variation of environmental temperature is of great interest.

In this paper, we report a long term stability of DMD-based diffractive beam steering under continuous operation of 360Hz. We also report a variation of mirror synchronization timing, consequently variation of diffraction efficiency under temperature variation of micro mirror array with ranges of 45 to 75 degrees C. We also discuss methods to keep

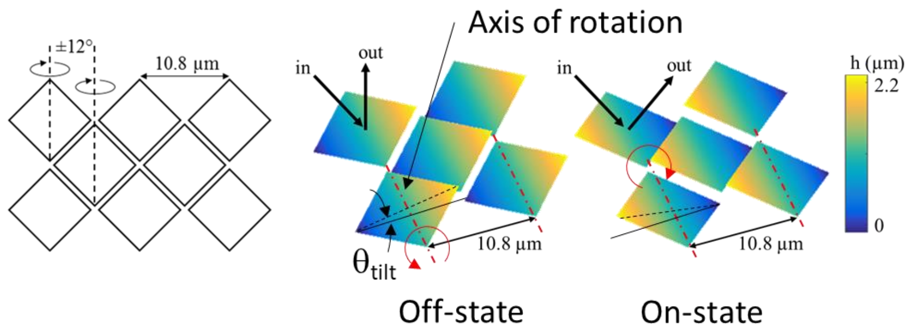
Emerging Digital Micromirror Device Based Systems and Applications XIII, edited by John Ehmke,
Benjamin L. Lee, Proc. of SPIE Vol. 11698, 116980I · © 2021 SPIE
CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2582899

the stability of DMD-based diffractive beam steering by adaptively controlling synchronization timing based on a look-up table under such temperature variation.

## 2. METHOD

### 2.1 Theory of discrete beam steering by digital micromirror device

DMD is considered as a binary spatial light modulator (SLM), where an array of pixels can flip between an "on" and "off" state by rotating +/- 12° about an axis defined by the diagonal of the mirror. In Fig. 1, the pixel arrangement of DMD is schematically depicted. Single pixel has a dimension of 7.637x7.637um with a 960x540 (horizontal by vertical) array. The micro mirrors are positioned in a diamond configuration with a corner-to-corner period of 10.8μm as shown in Fig. 1(a).




(a) (b)

Figure 1. Representation of the (a) 0.45-inch DMD diamond pixel geometry (Top View) with 10.8μm pixel period, mirror can flip between +/- 12°; (b) Schematic of "on" and "off" state of micro mirrors

Between the on and off state, there is a dynamic transitional state where micro mirror changes its tilt angle. The transition time of DMD is on the order of micro seconds. This unused transitional state of the DMD is utilized by a short-pulsed laser whose pulse duration is much shorter than the transition time of the mirrors. With the short-pulsed laser, the micromirror movement is "frozen" at an angle between the stationary "on" and "off" states. Thus, it is feasible to form a programmable blazed diffraction grating to discretely steer a laser beam with a collimated beam. It is also feasible to create a continuously scanned and diverging beam if the laser beam is focused on a single DMD mirror by eliminating the diffraction grating effects.

### 2.2 Timing in synchronization

Accurate synchronization between the ns laser pulse and mirror transition is needed for this beam steering technique to maximize the diffraction efficiency of discrete beam steering. Figure 2 shows a timing diagram for synchronizing pulse to DMDs' transitional state. First the mirror transition is initiated by triggering DMD. About 377μs after the external trigger pulse is applied to the DMD driver (Light Crafter 4500, Texas Instruments), mirror transition starts and it takes about 3μs to complete the transition. During the 3μs mirror transitional period, laser is triggered. At wavelength of 905nm, and with DLP4500, there are five mirror tilt angles that satisfies a blazed condition. Correspondingly at those timing, input laser is diffracted towards 5 diffraction orders, -2, -1, 0 +1 and +2$^{nd}$ orders.

The refresh rate in this experiment is 360Hz, and the approximated optimized internal time delay for each diffraction order are also listed in Fig. 2. We have experimentally verified that two global time delays, 377 and 380.25us exists for this specific model. Every time DMD is hardware reset, the global delay time changes from one to another value in a repeatable manner. This might be due to ambiguity in initialization logic.

As an inset of Fig. 2, laser synchronization timing is detailed. The timing $t_1$ to $t_5$ are additional delays to the global delay for each diffraction order from -2 to +2 order. The optimized internal delay time doesn't change, while global delay change between 377μs and 380.25μs in a repeatable manner upon restarting the unit.

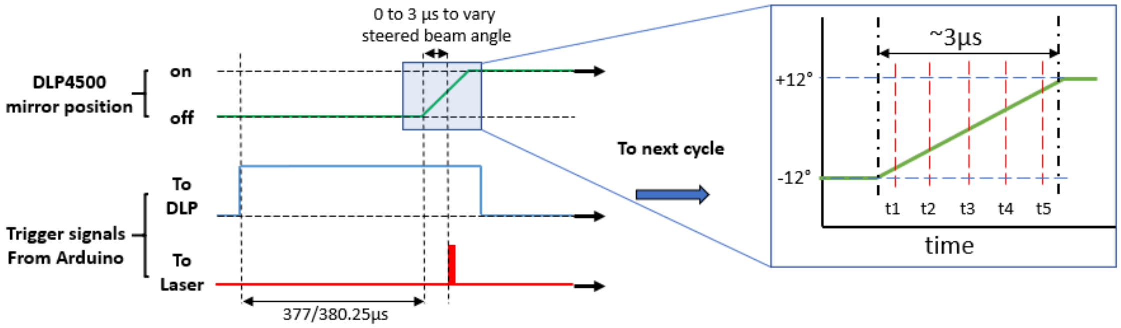



Figure 2. Timing diagram of DMD based diffractive beam steering with DLP4500. For global delay 377µs, $t_1$=0.5µs; $t_2$=1.25µs; $t_3$=1.875µs; $t_4$=2.375µs; $t_5$=2.75µs.

### 2.3 Evaluation of long term stability of DMD diffractive beam steering

Figure 3. shows a schematic of experimental setup for long term stability testing. A laser diode (LS9-220-8-S10-00, Laser Components) is collimated and illuminates the DMD with an 8ns pulse at an incident angle of 30 degrees. The incident beam is sequentially diffracted from -2$^{nd}$ to +2$^{nd}$ orderes into five diffraction orders. An Aluminum surface mirror (98% reflectivity) is placed in the path of each diffraction orders to redirect diffracted beams into three avalanche photodiodes (C12702-04 Hamamatsu) connected to a single oscilloscope (DS1104Z plus, RIGOL). From a cover glass on the top of DMD micromirrors, the beam reflected and follows the same path of the 0th diffraction order. In total, time profile of six signals, 5 diffractions and 1 cover glass reflection were monitored by oscilloscope.

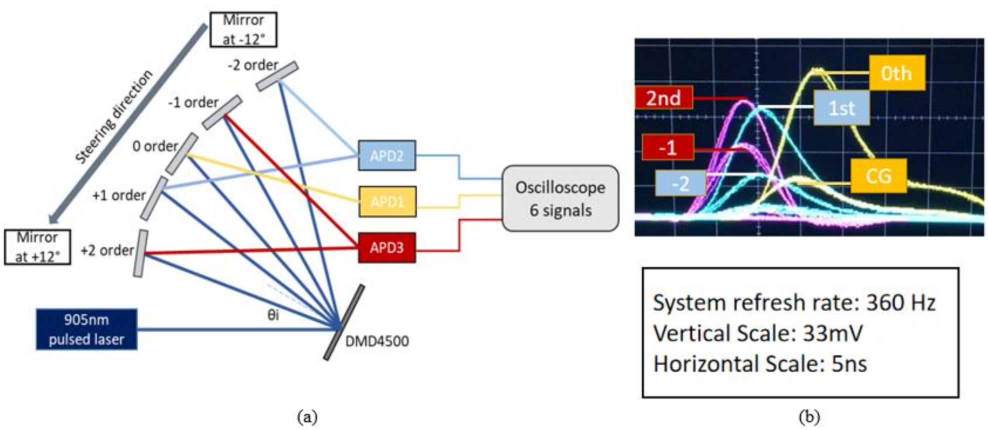
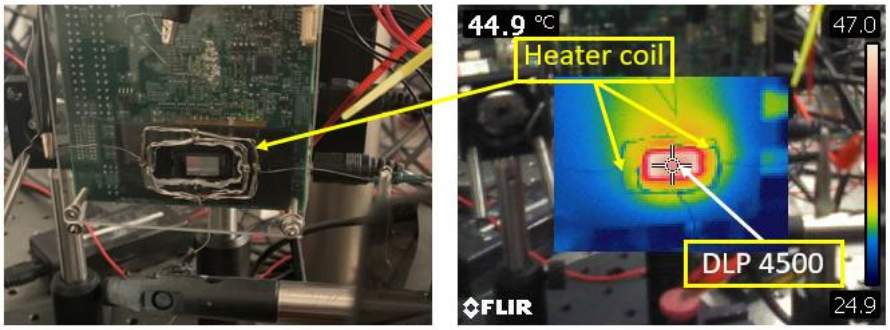



Figure 3. Schemetic of experimental setup.

### 2.4 Heat cycling testing

Figure 4 shows a picture of heat cycling testing setup. For the purpose of heat cycling test, two heating coils are placed around the DMD micro mirrors. Temperature is recorded by an infrared thermal imager (E40, FLIR).

By applying a current to each coil, the micromirror area of DMD is controlled as depicted in Fig. 6(b). The peak signal level of diffracted beam captured by APD, and DMD array temperature are plotted as a function of time in Fig. 6(a).




(a) (b)

Figure 4. (a) Setup of heat cycling test. Heating coils are places placed at the vicinity of DMD; (b) Temperature image captured by thermal imager

# 3. RESULTS

## 3.1 Long-terms beam steering test

Diffractive beam steering by DLP4500 was operated continuously for 350 hours under a room temperature (24 degrees C) without heatsink attached to DMD chip. In Fig. 5, the peak signal of five diffraction orders and cover glass are plotted with a linear trend line corresponding to each signal. The slope of each trend line is marked in red to evaluate the change in beam intensity. Since the signal of the beam reflected through the cover glass is not affected by time synchronization between DMD and laser pulse, the signal from cover glass serves as the base-line data for comparison with other beam intensity signals. As can be seen from Fig. 5, even though the light intensity signal fluctuates around the trend line, there is no significant downward trend from the beginning to end. The slope of all trend lines is less than the absolute value of 0.1. Therefore, we can say that the system has a high stability when working at room temperature for over 350 hrs.

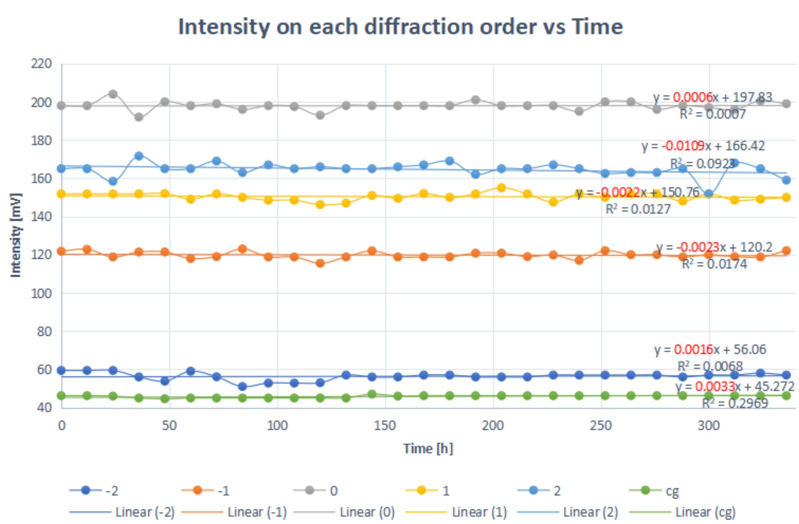



Figure 5. Results of continuously operating beam steering system under room temperature 25 degreee C

## 3.2 Heat cycling test

In the room temperature 25 degrees C, the temperature of DMD mirror array is 45 degrees C. Fig. 6(a) shows the peak signal of each diffraction order as a function of temperature change depicted in Fig. 6(b). When the micro mirrors' temperature exceeds 60 degrees C, the diffraction efficiency shows an obvious downward trend. And reached its lowest at 75 degrees C (the highest temperature given during the experiment). It was observed that the peak signal of the reflected light from the cover glass remained unchanged throughout the heat cycle. This proves that the experimental system was not, but only the change of the delay of the micromirror is affected by the temperature. This was also confirmed by re-adjusting delay time while DMD mirror surface temperature was 75 degree C.

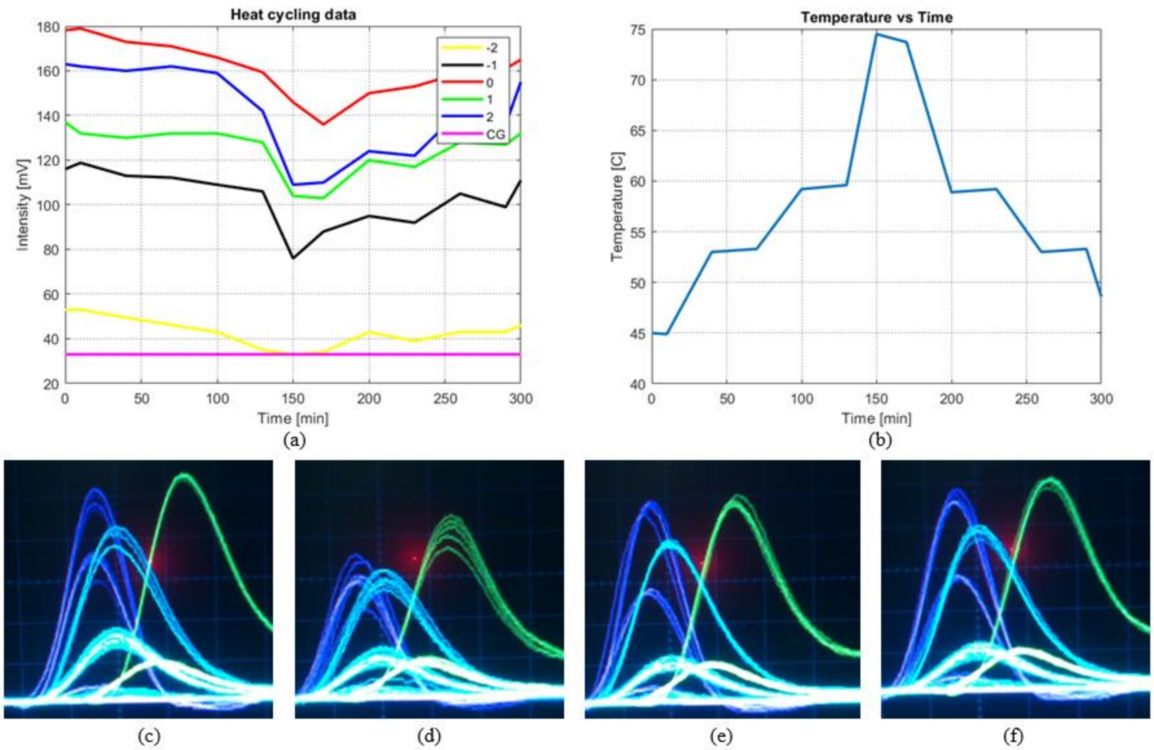



Figure. 6 Representation of (a). Peak signal of each of diffraction order during heat cycling; (b). Temperature on the micromirror surface during heat cycling; signal profile profiles (c) at 0min; (d) at 150min under highest temperature on DMD micromirror surface (75 degree C); (e) at 150min under highest temperature 75 degree C after increased the internal delay on each diffraction order by 125ns; (f) at 300min back to room temprature 25 degree C with 48 degree C on the micromirror surface of DMD

To confirm that the decrease of the peak signal is due to the variation of delay, we changed the internal delay at high temperatures and monitored diffraction efficiency of each orders. Figure 6(e) shows the signal profile under 75 degree C after increased by 125ns internal delay for each diffraction order. This tells us even though signal goes down under high temperature, it can be recovered by re-optimizing the delay through software, which is adjusting the internal time delay for different diffraction orders. At 75 degrees C, we observed the peak signal levels of all the diffraction orders were recovered to the level of array temperature of 45 degrees C.

Table 1. Signal change on each diffraction order after adjust different amount of internal delay times (in nanoseconds) under 75 degree C highest temperature

| **Temperature [℃]** | **Delay adjusted [ns]** | **2nd order [mV]** | **1st order [mV]** | **0th order [mV]** | **-1st order [mV]** | **-2nd order [mV]** |
|---|---|---|---|---|---|---|
| 75 | +62.5 | +35 | +25 | +20 | +10 | +3 |
| | +125 | +47 | +30 | +15 | -5 | _ |
| | +187.5 | +11 | _ | -3 | -6 | -2 |

Table 1, tabulates peak signal of each diffraction order concerning different internal delay increments. At 75 degrees C the results tells by increasing delay time, 125ns results in the highest light-strength increment for 1st and 2nd orders, increasing delay time results in the highest light-strength increment for 0th, -1st and -2nd orders. In our experiment, time precision is limited to 62.5 nanoseconds by clock cycle of the micro controller, Arduino Uno. The time resolution might not meet the optimum delay especially for -1st order. We also adjusted internal delay time at 60 degree C and 53 degree C. At 66 and 53 degrees C, the additional internal delay is less than that of the maximum temperature 75 degrees C.

## 4. DISCUSSION

There are several ways to maintain the stability of DMD diffractive beam steering method under temperature variation, besides physical cooling with heat sinks. According to the experimental data, we can optimize the internal delay time of each diffraction order as a function of temperature for example by using a lookup table to achieve a stable time synchronization at different temperatures. In the experiment, resolution of timing adjustment was limited by clock cycle of micro controller, 62.5ns. Even higher time resolution is feasible with a programmable timing element (for example DS1023, Dallas Semiconductor) between the Arduino and laser source which adds delay with 0.25ns timing precision [3, 4]. This allows the Arduino microcontroller to adjust delay with 0.25ns precision.

## 5. CONCLUSION

We evaluated stability of digital micromirror device based diffractive beam steering. We observed the high stability property of diffractive a beam steering after 350 hrs. of continuous operation. At the same time, we evaluated the effect of increased temperature of mirror array, especially on timing in synchronization between the laser pulse and micromirror transition time and quantified this effect by adjusting the internal delay. The results confirmed a stable and long term operation of DMD beam steering feasible by adjusting synchronization timing of ns- laser pulse to mirror transition in an adoptive manner for example using a look-up table.

## ACKNOWLEDGEMENTS

We acknowledge generous support by Semiconductor Research Corporation, Texas Instruments, Mitsubishi Electric and Tech Launch Arizona on this study of DMD based diffractive beam steering for lidar.

## REFERENCES

[1] Hans Dieter Tholl, "Novel laser beam steering techniques," Proc. SPIE 6397, Technologies for Optical Countermeasures III, 639708 (5 October 2006); https://doi.org/10.1117/12.689900

[2] "DLP7000 DLP® 0.7 XGA 2x LVDS Type A DMD", Texas Instruments, Literature Number: DLPS026F – AUGUST 2012–REVISED JUNE 2019

[3] Smith, B., Hellman, B., Gin, A., Espinoza, A., and Takashima, Y., "Single chip lidar with discrete beam steering by digital micromirror device," Opt. Express 25, 14732–14745 (Jun 2017).

[4] Joshua Rodriguez, Braden Smith, Eunmo Kang, Brandon Hellman, Guanghao Chen, Adley Gin, Alonzo Espinoza, and Yuzuru Takashima "Beam steering by digital micro-mirror device for multi-beam and single-chip lidar", Proc. SPIE 10757, Optical Data Storage 2018: Industrial Optical Devices and Systems, 107570F (14 September 2018); doi: 10.1117/12.2323757; https://doi.org/10.1117/12.2323757

[5] Yajun Wang, Bhaskar Bhattacharya, Eliot H. Winer, Peter Kosmicki, Wissam H. El-Ratal, Song Zhang, Digital micromirror transient response influence on superfast 3D shape measurement, Optics and Lasers in Engineering, Volume 58, 2014, Pages 19-26, ISSN 0143-8166, https://doi.org/10.1016/j.optlaseng.2014.01.015. (https://www.sciencedirect.com/science/article/pii/S0143816614000165)

[6] "TI DLP® LightCrafter™ 4500 Evaluation Module User's Guide", Texas Instruments, Literature Number: DLPU011F July 2013–Revised July 2017

[7] Sontheimer, A.B.. (2002). Digital Micromirror Device (DMD) hinge memory lifetime reliability modeling. 118 - 121. 10.1109/RELPHY.2002.996622.

[8] Douglass, Michael. (2003). DMD reliability: a MEMS success story. Proceedings of SPIE - The International Society for Optical Engineering. 4980. 10.1117/12.478212.