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ABSTRACT

A novel method of beam steering, utilizing a mass-produced Digital Micromirror Device (DMD), enables a reliable single chip Light Detection and Ranging (LIDAR) with a large field of view while having minimum moving components. In the single-chip LIDAR, a short-pulsed laser is fired in a synchronous manner to the micromirrors rotation during the transitional state. Since the pulse duration of the laser pulse is substantially short compared to the transitional time of the mirror rotation, virtually the mirror array is frozen in transition at several discrete points, which forms a programmable and blazed grating. The programmable blazed grating efficiently redirects the pulsed light to a single diffraction order among several while employing time of flight measurement. Previously, with a single 905nm nanosecond laser diode and Si avalanche photo diode, a measurement accuracy and rate of <1 cm and 3.34k points/sec, respectively, was demonstrated over a 1m distance range with 48° full field of view and 10 angular resolution. We have also increased the angular resolution by employing multiple laser diodes and a single DMD chip while maintaining a high measurement rate of 3.34k points/s. In addition, we present a pathway to achieve 0.65° resolution with 60° field of view and 23k points/s measurement rate.

Keywords: optics, photonics, lasers, MEMS, DMD, LIDAR

1. INTRODUCTION

Laser beam steering technology is essential for Light Detection and Ranging (LIDAR) systems. For this reason, beam steering technologies have been actively researched. Along with mechanical and completely non-mechanical beam steering, Micro-Electro-Mechanical-Systems (MEMS) is an emerging beam steering field that is especially suitable for LIDAR systems. Mechanical scanning including gimbals, fast-steering mirrors, Risley prisms, rotating polygon mirrors and gratings have been used for wide wavelength ranges.[1] Although mechanical beam scanning modalities are widely adopted, having fewer or no moving parts and smaller component inertia is more desirable for fast and compact beam steering devices so that size, weight, cost, and power consumption can be reduced.[2,3] These qualities are especially required for autonomous vehicle and robotics applications. In contrast, completely non-mechanical scanning such as programmable spatial light modulators, modulo 2π optical phased arrays, solid state phase arrays, and liquid crystal electro-optic scanners are emerging, and are now actively researched.[2,4–7]

In terms of reducing small component weight and inertia to fast beam steering, Micro-Electro-Mechanical Systems (MEMS) are promising due to their small size and weight, low production cost, high energy efficiency, and applicability to wide wavelength ranges. These MEMS devices include single resonant mirrors and shifting lenslet arrays.[2,8,9] However, in LIDAR applications for autonomous vehicles, a large steering angle as well as large beam size are needed to cover a large angle of scanning and minimize beam divergence due to diffraction. Unfortunately, resonant mirrors and shifting lenslet arrays are limited in angular range and maximum accommodated beam size. Current high-end resonant mirror MEMS scanning systems have moderate fields of view at 36° and scan rates of

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21 kHz.[2,10] However, a resonant mirror's maximum beam diameter is only increased at the expense of decreasing the maximum scan rate.[9] An optical amplification of the steering angle by an inverse telescope design has been reported; however, this design requires a reduced beam diameter to conserve the Lagrange invariant, which would limit the effective delivery of light over large distances due to beam spreading by diffraction.[11,12]

As our group previously demonstrated, beam steering by Digital Micromirror Device (DMD) with a short pulsed laser is not only possible, but can be implemented in highly accurate scanning LIDAR systems.[13] This beam steering technique has a high beam steering efficiency (close to 100% in theory), a larger beam size (same as DMD area), a wide field of view (48°), and a high scan rate (tens of kHz) while minimizing the number of moving parts. The limitation of this approach, however, is that the maximum number of scanning points is limited to about 5 to 9 points for a wavelength range of 0.5 to 1μm with a commercially available DMD. We now propose and demonstrate increasing the angular resolution of the LIDAR system by implementing multiple laser diodes.

2. MULTI-BEAM AND DISCRETE BEAM STEERING BY DMD

2.1 DMD Beam Steering Theory

In Fig. 1(a), the DMD is schematically depicted. This beam steering setup utilizes a 608x684 (horizontal by vertical) DMD chip (DLP3000, Texas Instruments). The micromirrors are positioned in a diamond configuration with a corner-to-corner period of 10.8μm as shown in Fig. 1(a). On this DMD, an array of micromirrors flip between an "on" and "off" state, shown in Fig. 1(b)-(d), by rotating ±12° about an axis defined by the diagonal of the mirror. Thus, a DMD is designed for binary spatial light modulation and is not intended to be used for angular beam steering, unless additional optics to convert the spatial modulation to angular modulation are incorporated at the expense of light throughput.[14]

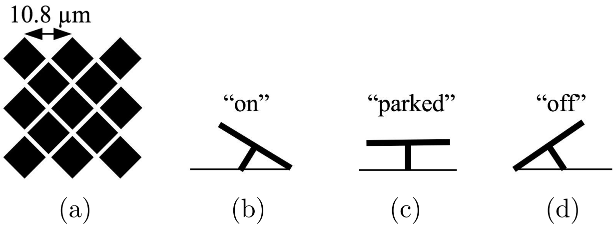

Figure 1. Representation of the (a) DMD diamond pixel layout (Top View); (b) a mirror in the "on" position at +12° (c) a mirror in the "parked" position at 0° when the DMD is powered down; (d) a mirror in the "off" position at -12°.

The unused transitional state of the DMD is utilized with a short-pulsed laser with a pulse duration much shorter than the transition time of the mirrors. For a particular steered beam angle, there is a corresponding delay between laser diode activation and DMD mirror flipping. The micromirror movement is frozen at an angle between the stationary on- and off-states with the pulsed laser. Thus, it is feasible to form a programmable and highly efficient blazed diffraction grating to discretely steer the laser beam.

2.2 Multiple Beam Scanning

Pulsed light from a 905nm and 8ns pulsed laser module (LS9-220-8-S10-00, Laser Components, Germany) is collimated by a 20X and 0.4 NA microscope objective lens, which illuminates DMD. The tilt timing of the DMD mirror is synchronously controlled with the laser pulse by an Arduino microcontroller with a DS1023 delay IC chip. By adjusting the time delay, each of the pulses are diffracted into one among 5 discrete diffraction orders with high diffraction efficiency, theoretically close to 100%. The number of scanning points is increased by multiple laser sources as depicted in Fig. 2. Two additional laser modules are added with ±3.3°of incident angle deviated from the central laser path. This configuration allows qasi-evenly-spaced angular spacing. Figure 3 is a simulated intensity distribution over the 50° field of view by Huygen-Fresnel integral. Each mirror was modeled as a series of point sources with an associated phase and optical path length (OPL) induced by the tilt of mirror while taking into account the angle of incidence of the laser module.

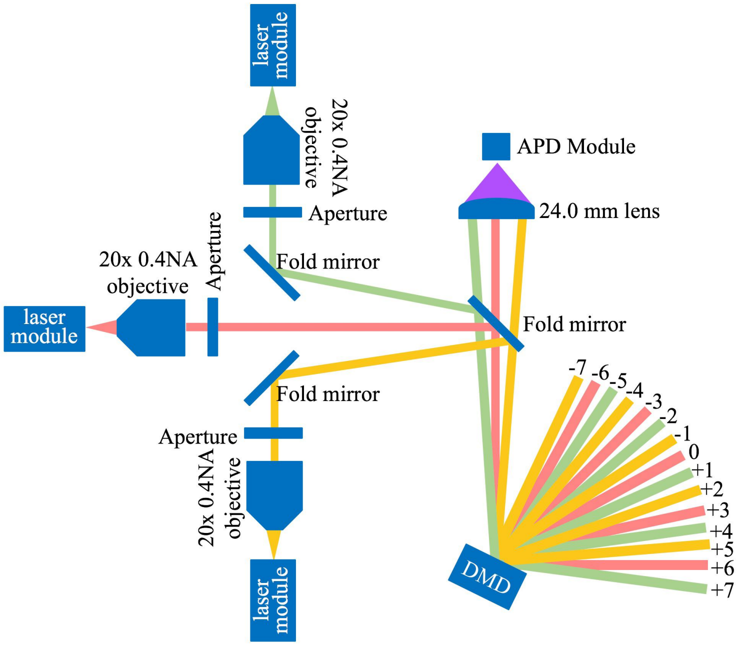

Figure 2. Schematic of setup utilizing 3 laser diodes.

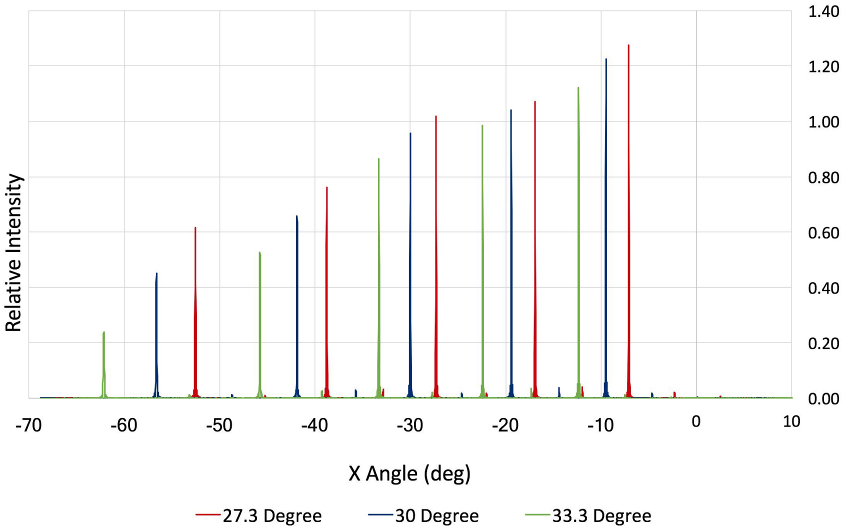

Figure 3. Simulated intensity profile at far-field from three laser diodes. Intensity is normalized to peak intensity of 0th order beam from the central laser module.

3. RESULTS

3.1 Beam Steering

The pulse timing from the 3 laser diodes modules is synchronized to transition of micro mirrors between on- and off-state by Arduino micro controller by the control sequence depicted in Figure 4. Figure 5 shows a picture of 15 beam spots. A screen was placed at a distance of 50cm from the DMD, and the scanned spots are captured as a movie. Then, video frames corresponding to each of the scanning spots are cropped. At the bottom of the picture, a long exposure of all 15 scanning spots is depicted.

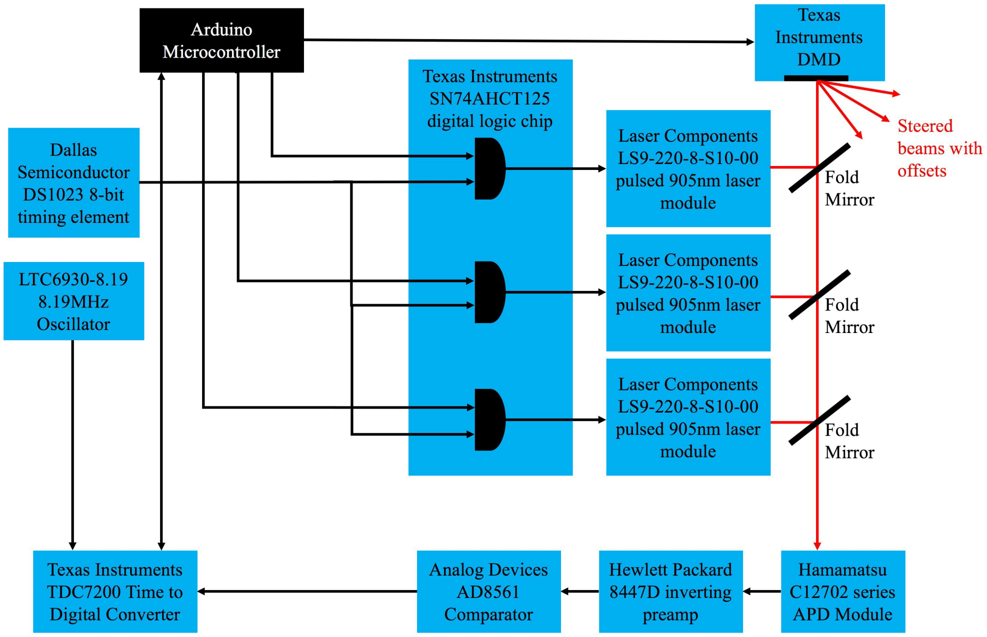

Figure 4. Block diagram of system operation with circuitry.

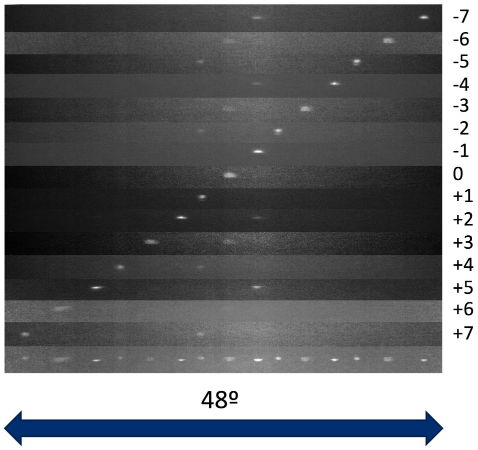

Figure 5. Total of 15 scanning spots from top to bottom, scanning point +7 to -7 depicted in Fig. 2(c) are captured. At the bottom of the picture, long exposure to show all the 15 scanning spots are depicted.

3.2 Range Finding

To make time of flight measurements for the LIDAR application, an avalanche photodiode (APD) (C12702, Hamamatsu) and a fold mirror were added to the single LD optical setup (similar to Fig. 2). In this experiment, multiple laser diodes were added to the system to demonstrate a pathway to increase the number of diffraction orders in such a system. The configuration shown in Fig. 2 involves three 905 nm laser diode module (LS9-220-8-S10-00, Laser Components, Germany) directed towards the DMD with a ±3.3° incident angle separation from the central beam to ensure that the points are equally spaced. The ±3.3° incident angle separation generates equal spacing because diffraction orders are spaced approximately 10° apart when using 905 nm light. To save space, fold mirrors were used to physically offset the three laser diodes while maintaining the correct angular spacing of the beams.

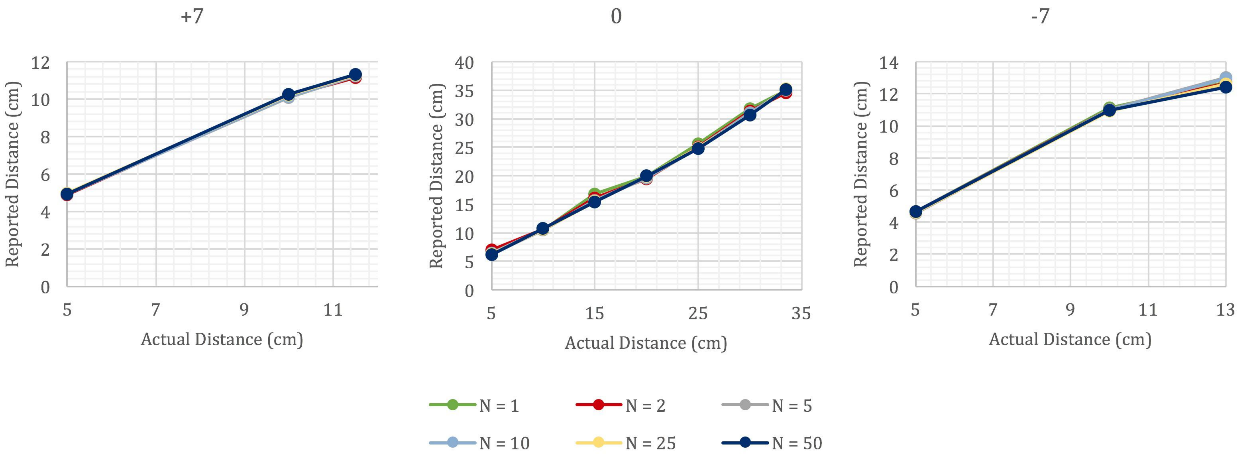

Figure 6. Distance measurements of objects placed in +7, 0, and -7 diffraction orders. Measurement increments of 5cm plus maximum distance measurable with system taken with averaging between $N = 1$ and $N = 50$ shown.

In Figure 6, distance measurement results from the central and outer orders are reported. As an object, we used pieces of cardboard aligned at each of the diffraction orders. The point denoted as +7 in Fig. 2 corresponds to the beam denoted as +7 in Figs. 6. Likewise, The point denoted as -7 in Fig. 2 corresponds to the beam denoted as -7 in Figs. 6. The distance was measured at 5cm increments in each case and additionally at the maximum measurable distance with the laboratory setup. As expected, the maximum measurable distance decreases in the outer orders since less power is redirected to them. The data accuracy stays fairly linear, with the accuracy staying well within ±2cm at all points with no averaging as shown in Fig. 6. With even some averaging, the data is more accurate.

4. DISCUSSIONS

The number of scan points is limited not only to a certain number of diffraction orders generated per laser diode, but also to the number of laser diodes used. With the current DMD (DLP3000), five diffraction orders are available when using a single 905 nm laser at a 30° incidence angle. The number of scanning angles can be increased by employing a larger DMD micromirror pitch and/or a shorter wavelength.[13] The limitations of two commercially available DMDs under ideal conditions for certain wavelengths of light are shown in Table 1. However, it is evident that we can accurately measure distance over 175 m with a higher scanning rate of up to (256 lines/s) x 90 (points/line) = 23k points/sec and a field of view over 60° with 0.65° angular resolution.

Table 1. Performance summary for two DMD types and two wavelengths of light.[13]

DMD Model	Wavelength	Range	N_{LD}	N_{ord}	Total Number of Scan Angles	FOV	Resolution	Scan Rate (lines/s)
DLP3000	905nm	55m	5	5	25	49°	1.9°	160
DLP3000	1550nm	55m	8	3	24	50°	2.1°	167
DLP9500	905nm	175m	11	7	77	48°	0.62°	299
DLP9500	1550nm	175m	18	5	90	60°	0.65°	256

Currently, the angular spacing among multiple laser diodes is limited by the housing size of the laser diode modules and/or optics to collimate laser beam. Thus, it is not feasible to accommodate 18 lasers. Through an array of laser chips mounted on a common substrate with a single collimating lens solves the problem. The scanning speed is limited by the refresh rate of the DMD since a single pulse is launched per single rotation of the mirror. Thus, to scan 15 points, 15 DMD mirror flips is required. However, this requirement is not difficult. For an even faster scan rate, multiple pulses can be launched per single rotation of the DMD mirror that increase the scanning speed by a factor of the total number of diffraction orders.

5. CONCLUSIONS

Multi-Beam Single-Chip DMD LIDAR provides a unique pathway to long distance range finding by leveraging commercially available Digital Micromirror Device. As a proof of concept, 15 points of range finding is demonstrated by using three 905nm pulsed laser diode modules. With an array of laser diodes and state of the art detectors, we estimated that the system provides a solution for long range, high speed, and high angular resolution distance measurement without bulky scanning or receiving optics.

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