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Solid-state beam steering with adaptive side lobe rejection and enhanced angular throw of MEMS phase SLM by angular spatial and phase combined modulation

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ABSTRACT

Laser beam steering is an essential function for LiDAR. Phase Spatial Light Modulator (SLM) provides a capability of steering beam in a fast and random-access manner but suffers from limited FOV and side lobes. In this paper, we present a DMD (Digital Micromirror Device)-PLM hybrid beam steering concept that features high resolution, large-FOV, and side-lobe free beam steering.

Keywords: LiDAR, Beam steering, Phase Light Modulator, MEMS, Digital micromirror device.

1. INTRODUCTION

Laser beam steering is widely adopted for application like lidar and display and scientific measurement. Especially for lidar application, high efficiency, fast scanning rate, fast scanning range and larger aperture supported by a large device area is highly desirable. Devices such as mechanical scanner system, Liquid Crystal on Silicon (LCoS) and Micro-Electro-Mechanical System (MEMS) mirrors have been used for beam steering [1-2].

Steering beam in a quasi-continuous manner by phase-only Spatial Light Modulator (SLM) has been reported [3], by Computer Generated holograms (CGHs) having non-integer multiple of pixel period. The phase profile of CGH for single point beam steering is a staircase approximated saw-tooth phase profile. As far as periodicity of CGH is integer multiple of pixel period, and with enough phase levels to approximate saw-tooth phase profile, diffraction efficiency towards 1st diffraction orders is high. However, diffractive beam steering suffers from side-lobes and DC (non-diffractive) components due to aforementioned non-integer pixel periods, limited number of available phase levels, and their non-linearity. Such side-lobes and DC component is a potential source of false signal, such as a ghost image in lidar detection.

In addition, not the side-lobes and DC component, another and well-known limitation of SLM based beam steering is limited angular throw. The first order diffraction angle is given by λ/d, where λ is wavelength and d is periodicity of the CGH. SLMs having pixel period is larger than the wavelength limits angular throw of beam steering within couple of degrees.

Recently, we demonstrated that a pulsed illumination synchronized to movement of MEMS mirror array extends the angular throw from several degrees to tens of degrees [4]. Based on the principle, In this paper, we proposes a concept of hybrid beam steering which enables a side-lobes free and wide FOV beams steering. In this concept, single MEMS-SLM (Digital Micromirror Device, DMD) is used for a dual use, a) enhancement of the angular throw of phase CGH based beam steering, and b) side-lobe and DC component rejection. The concept enables side-lobe and DC component free, large angler throw, and high-resolution beam steering.

In section 2, we analyze side-lobes and DC components appearing with CGH-based quasi-continuous beam steering. In particular, Texas Instruments Phase Light Modulator (PLM) is used as a model followed by reviewing the theory of operation of DMD-based beams steering. In section 3, we address a concept of the hybrid beam steering to provide a wide-FOV and side lobes beam steering system. In section 4, we show experimental results of beam steering based on the proposed concept.

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2. BEAM STEERING BY PHASE MEMS SLM

To generate Computer Generated Hologram (CGH) displayed on a Phase Light Modulator (PLM), Gerchburg and Saxton (GS) algorithm and deterministic CGH calculation are both adopted [3]. GS algorithm requires iteration of calculation and is time prohibitive for the application such as lidar with random-access beam steering. In contrast, deterministic method requires much less time to calculate the CGH while providing similar levels of diffraction efficiency as far as CGH is designed for single beam steering applications.

The CGH modulates phase of laser in a 2-dimensional and a pixelated manner with discrete number of phase levels [5]. In deterministic method a sawtooth shaped phase profile with a modulation depth of 2π provides the highest diffraction efficiency and is known as a blazed grating. The 1st order diffraction angle is determined by λ/d where λ is a wavelength of and d is a periodicity of the phase pattern. Since phase SLM is a digitally controlled device, the spatial phase profile in implemented in a discretized manner both in phase level and spatial pattern. The continuous and sawtooth "blazed" phase profile is approximated by a stair-case phase profile. The diffraction efficiency of such stair-case profile is analytically formulated, and is given by,

$$\eta_n = \left(\frac{sinc\left(\frac{n}{m}\right) sinc\left(\frac{\phi_0}{2\pi} - n\right)}{sinc\left[\frac{1}{m}\left(\frac{\phi_0}{2\pi} - n\right)\right]} exp\left(j\left[\frac{(1+n)\phi_0}{2m} - n\pi\right]\right)\right)^2 \quad (1)$$

where n is the diffraction order of the blazed grating, m is the number of the discretization level, and ϕ_0 is the maximum phase modulation.

Figure 1 plots a diffraction of each diffraction order of stair-case approximated phase CGH with period of $d = 3p$, where p is period of SLM. From the stimulation, most of the power go to the diffraction order -1, while there is still some power distributed to diffraction order 2 ,1 ,0 and -4 that appears as side-lobe diffraction pattern.

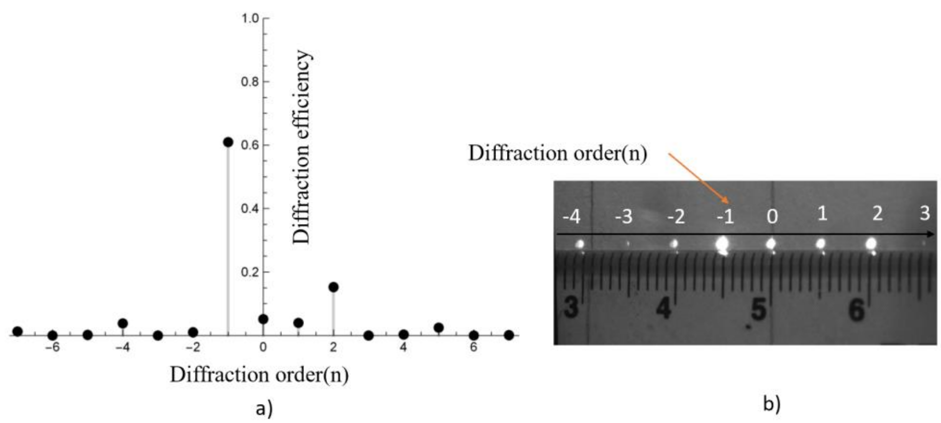


Figure 1. The stimulation result (a) and diffraction pattern (b) of a blazed grating with d = 3p. The Diffraction pattern satisfied the stimulation result.

3. FOURIER FILTERING BY MEMS SLM

The side-lobes and DC components can be Fourier filtered by secondary SLM such as Texas Instruments Digital Micromirror Device (DMD). DMD has an array of micromirrors with $10.8\mu m$ corner-to-corner pitch. The micro mirror tilts between +12°and -12° binary states, with respect to a flat "parked" state in a programmable manner. Figure 2 show the three states of the micromirror. This feature enables DMD to select the beam of interest while reject the side lobes by using the combination of "on" and "off "state.

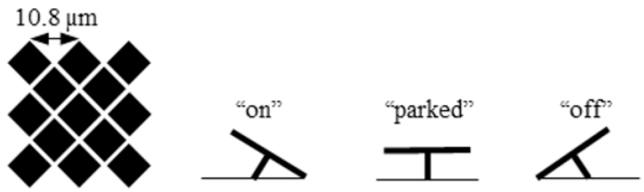


Figure 2. Simplified representation of DMD micromirrors diamond pixel layout and the three states of micromirror.

By placing the MEMS SLM at the Fourier plane of the phase SLM, the side-lobes and DC component are eliminated by adaptively updating the spatial pattern of SLM to make it as a dynamic mask. The Fourier filtering is usually employed when the mirrors are in static states, "off" or "on". However, the Fourier filtering is also feasible while mirrors are in the transitional states between "off" and "on". The transitional state of mirror array of DMD also enables wide beam and image steering [4]. While mirror arrays are transitioning between +12° and -12, with a short-pulsed laser, the micromirrors' rotation is frozen in mid-transition, which forms a programmable blazed grating. During the transition of DMD mirrors, the timing of laser pulses illuminating the DMD is controlled redirect holographic image to enlarge the viewing zone. Experimentally, the viewing zone was substantially increased to about 40° using the DMD with a pixel pitch of 13.68 µm.

. 3. PLM-DMD HYBRID BEAM STEERING

The challenges in phase SLM-based beam steering, narrow steer angle, side-lobes and DC components are mitigated by combining two MEMS-SLMS, Phase Light Modulator (PLM) and DMD. Figure 3 shows a block diagram of the system. In this system a pulsed laser illuminates PLM with CGH pattern generated by deterministic method. Focusing lens forms a Fourier pattern of PLM on the DMD placed at the focal place of the lens. Based on the Fourier transform of the CGH pattern, a "masking" pattern is displayed on the DMD surface. Laser pulse illuminates the mask pattern while DMD mirror arrays are in transition to display to static image. In this manner, side-lobes and DC components are rejected while the beam of interest is picked up. The picked-up beam of interest is steered to one of the diffraction orders of DMD with high diffraction efficiency [2]

Since DMD is used for dual use, Fourier filtering and re-direction of beam of interest towards one of the diffraction orders supported by DMD, synchronization of pulse to DMD and PLM with tens of nano sec is required [2]. Microcontroller (Arduino uno) controls the timing of pulsed laser, PLM and DMD controller while coordinating operation among three. For example, controller is programmed to display CGH on PLM before the triggering the movement of DMD, and pulsed laser is fired while DMD mirrors are in transition to display Fourier mask pattern.

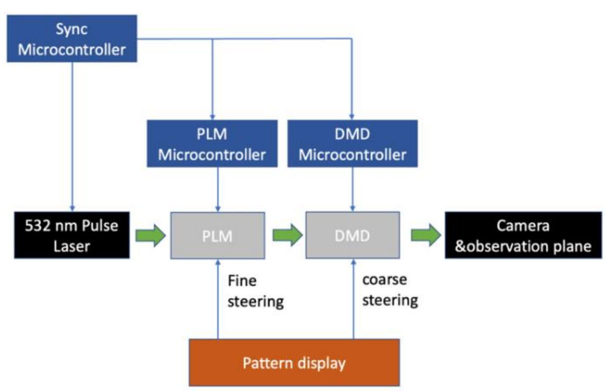


Figure 3. Block diagram of the PLM-DMD hybrid beam steering concept.

4. EXPERIMENT RESULT

Video 1 shows experiment result of beam steering by employing DMD as a dynamic Fourier filter and replicating fine steering pattern by PLM over 5 diffraction orders. On PLM, a binary CGH with pixel period of 2 was displayed. In Fig. 5, diffraction pattern of PLM with the CGH is shown. There, no Fourier filtering nor FOV expansion is employed. For binary phase CGH, +1st and -1st diffraction appears in a symmetrical manner along with DC component. Also, the diffraction angle is limited to +/- 1.4 degrees. In Video. 1, in the beam steering pattern, one of the diffraction orders (+1st order) and DC component is filtered out by DMD. Also scanning field of view is expended over 5 diffraction orders. In this manner, wide FOV, DC and side-lobe free beam steering is feasible by the proposed optical architecture.

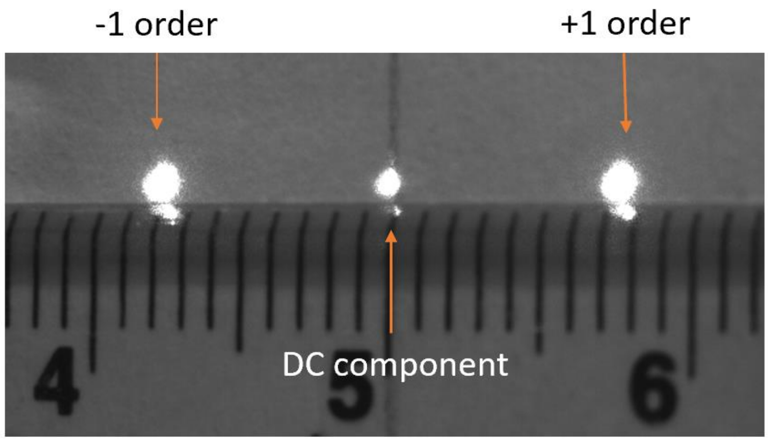
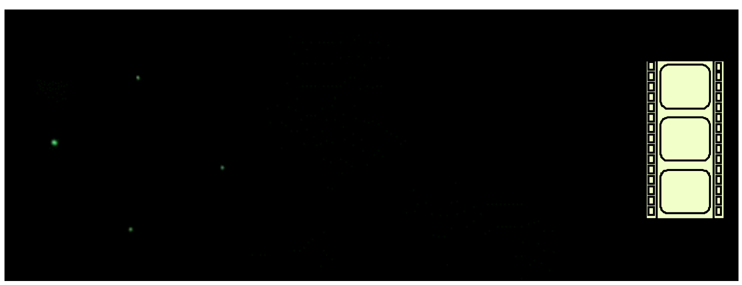


Figure 5. PLM-only beams steering for period number *d* = 2p.



Video 1. DC-free, Side-lobe free and Wide FOV beam steering result with PLM-DMD hybrid beam for period number *d* = 2p. http://dx.doi.org/10.1117/12.2610597.1

5. CONCLUSION

In this paper we propose a concept of DMD-PLM hybrid beam steering. Beam steering by PLM suffers from limited FOV, side-lobes as well as DC component. By employing DMD as Fourier filter and FOV expander to, a wider and DC/side-lobe free beam steering is feasible.

6.ACKNOWLEDGEMENT

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