P-158: DMD Illumination Using Diffractive Optical Elements

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Abstract

We investigate two optical setups designed to illuminate Digital Micro-mirror Device™ (DMD). The optical setups basically consist of one or two Diffractive Optical Elements (DOEs) and a vibrator. Laser is taken as a light source. We discuss various design aspects, and we focus on problems of speckle reduction and full-color DMD illumination using DOEs. Preliminary experimental results and measurements, which were obtained with DOEs fabricated on a transparent fused silica substrate by use of standard photolithography, are included.

1. Introduction

The lamps with small arc length have been a conventional source in image projection applications. However, lasers are attractive alternative light sources to arc lamps for such systems. Laser illumination allows a wider color expression and low-cost efficient optical systems. On the other hand, speckle noise makes it difficult to realize potential advantages of lasers. Speckle is a random intensity distribution that is detected by an observer's eye when coherent light is reflected from a rough surface. Due to speckle, the image on the screen has granular appearance that masks the image information. The usual speckle reduction techniques [1, 2] include incoherent wavefront summation of the resolution elements of the projected diffuser within one resolution element of the observer's eye. In this work we use DOE to perform such incoherent wavefront summation. The considered projection system contains DMD as an optical modulator. The DMD modulates a light beam from a light source with two-dimensionally arrayed micro-mirrors.

2. Design and Experiment

A typical optical arrangement for illumination of DMD using a lamp is shown in Figure 1. Light-pipe integrators (LPIs) or lenslet integrators are generally used.

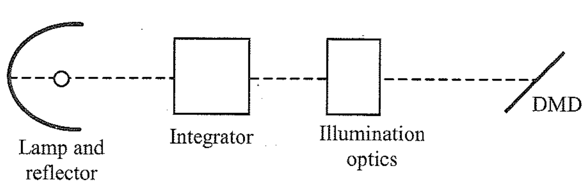

Figure 1. Optical arrangement for illumination of DMD with a lamp source

When employed with lamps, LPI is usually more preferable solution than lenslet integrator [3]. However, to achieve sufficient uniformity in laser projection system, it is necessary to use LPI with a larger length. In this case, lenslet integrator is a more flexible solution. Laser projector with rotating diffuser and lenslet integrators had been investigated to realize uniform illumination and reduce speckle contrast in LCD based projection system [4].

In this work we examined DMD illumination scheme in which DOEs perform the functions of duffuser and integrator (see Figure 2).

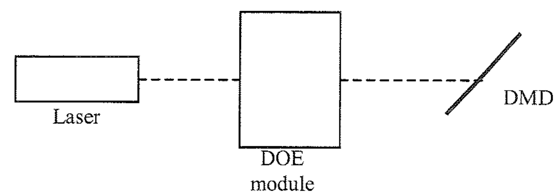

Figure 2. General optical setup of DMD illumination with a laser source

The employment of DOE in the raster scan laser projection system had been already reported [2]. DMD provides advantages over raster scan systems. Firstly, there is no flash noise due to non-stability of laser parameters. Secondly, scanning block is not required.

2.1 Parallel Laser Illumination

In the first optical setup we investigated parallel laser illumination of DOE.

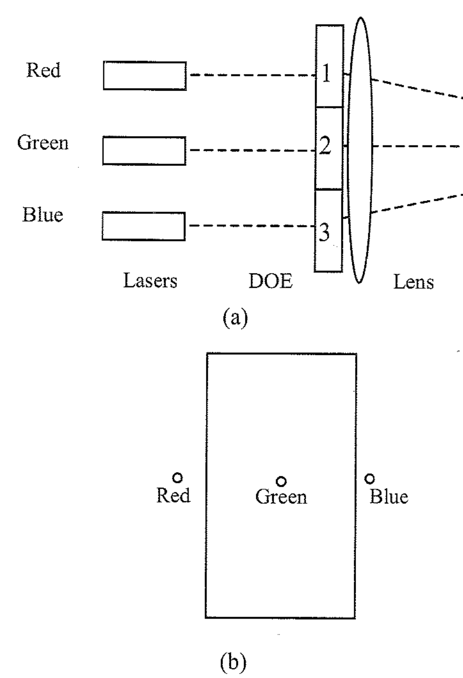

Figure 3. Schematic diagram of (a) DOE parallel illumination, (b) DMD image rectangle and 0th diffraction orders positions for each color laser beams

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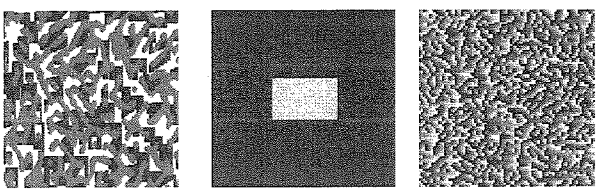
In this case DOE consists of three equal size parts 1, 2, and 3 as shown in Figure 3 (a). Size of each part is 3.3x3.3 mm. In experiment diode-pumped solid-state (DPSS) laser, with wavelength 532 nm, illuminates the central part 2 of DOE that is on-axis element. On-axis DOE projects 0^{th} diffraction order in the center of the generated image. Parts 1 and 3 of DOE are off-axis elements. Beamlets number required to cover DMD rectangle in the image plane is different for each part of DOE. The etch depth is the same for all parts and corresponds to green light wavelength. It permits to fabricate three parts of DOE in one step. The 0^{th} diffraction orders for red and blue lasers fall outside DMD area and don't decrease the DMD image uniformity (see Figure 3 (b)).



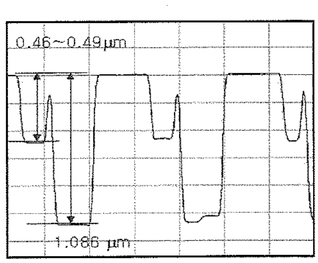
(a) (b) (c)

Figure 4. (a) Designed three-levels DOE profile; (b) simulated DMD image, (c) fragment of eight-level DOE profile

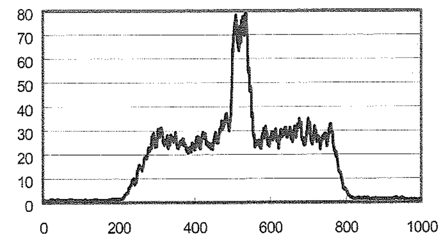
DOE profiles were calculated with modified iterative Fourier-transform algorithm [5]. In the next design step DOE profiles were enhanced with simulated annealing method [6]. The mask of designed three-level DOE is shown in Figure 4(a). The three-level DOE permits to reduce color aberrations and to decrease sensibility of two-level DOE to fabrication etch depth errors [7]. Gray color in figure denotes π etch depth, white and black colors mean 0 and 2π depths, respectively. Figure 4(b) shows simulated intensity distribution in the image plane. Simulated uniformity error is 2.1% and energy efficiency is 78.8%.

The three-level DOE, like two-levels DOE, allows to generate only on-axis symmetrical images. Greater number of DOE profile levels is necessary to realize an off-axis element. Thus, there were designed off-axis DOE with 4, 8, and 16 profiles levels (see Figure 4 (c)). Simulation showed that the bandwidth of eight-level DOE is sufficient to achieve about 95% theoretical efficiency when a separate beamlet illuminates each DMD micro-mirror.

To verify our approach three-level DOEs were fabricated. Binary mask photolithography in combination with reactive-ion etching was used to produce multilevel profiles. Fused silica was the material of DOE substrate.



(a)



(b)

Figure 5. Experimental measurement results: (a) three-levels fabricated DOE profile, (b) generated intensity profile

Figure 5 (a) illustrates a fragment of fabricated three-level DOE. One can see the etch depth errors and errors due to masks misalignment. Experiments confirm that the illumination scheme shown in figure 3 has disadvantages. The fabrication etch depth errors produce high 0^{th} diffraction order for part 2 of DOE (see Figure 5(b)). It destroys the uniformity of DMD illumination. Besides, the speckle reduction is not sufficient for this optical setup.

2.2 Sequential Laser Illumination

The second optical arrangement is investigated to efficiently reduce speckle noise. In this optical setup (see Figure 6 (a)) laser beams are combined on a common optical axis by dichroic mirrors.

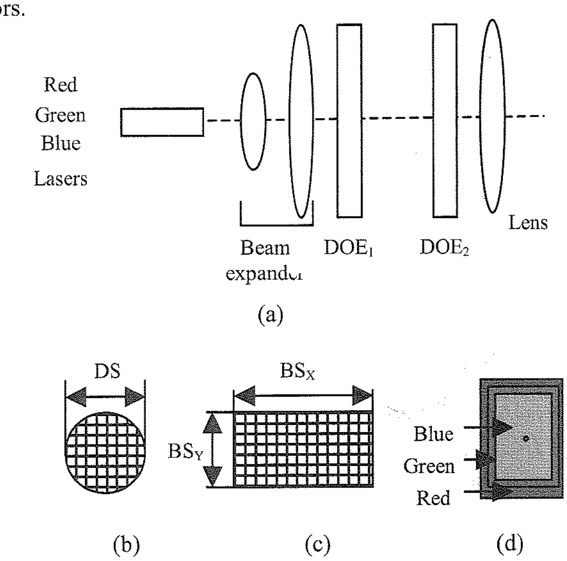
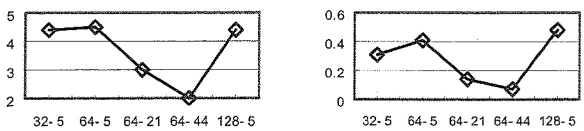


Figure 6. Schematic diagram of (a) optical setup with despeckling DOE_1 and beam-shaper DOE_2, (b) far-zone image for DOE_1, (c) far-zone image for DOE_2 (d) DMD image rectangles and 0^{th} diffraction orders for each color laser beams

DOE module for the second arrangement contained two DOEs. DOE_1 generates on-axis circle with diameter *DS* diffraction orders (see Figure 6 (b)). This DOE is supposed to perform the speckle reduction. DOE_2 generates on-axis rectangle-with size $BS_X \times BS_Y$ diffraction orders (see Figure 6 (c)). This DOE performs the beam-shaping function. Figure 6 (d) schematically shows DMD rectangles for each color.

Five DOE_1 with various unit cell sizes and *DS* parameter values (1st DOE - *32* um unit cell size and *5* DS value, 2nd - *64* and *5*, 3rd - *64* and *21*, 4th - *64* and *44*, 5th - *128* and *5*) were fabricated. Fabricated DOE_2 produced rectangle with *101*×*51* diffraction orders.

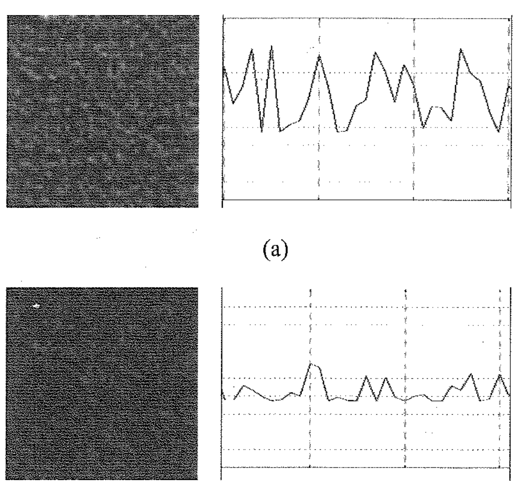
Figure 7 (a) shows speckle reduction value for each DOE_1 with fixed DOE_2. One can see that speckle reduction value doesn't depend on DOE_1 unit cell size. However there is clear dependence on the number of beamlets that produced by DOE_1.



(a) (b)

Figure 7. Experimental measurement results for each fabricated DOE_1 with fixed DOE_2: (a) speckle reduction value (%), (b) energy efficiency (1 corresponds to 100%)

The projection screen was a white typing sheet. A CCD camera that operates in the linear regime was used to capture the speckle images. The camera aperture size was about 3 mm that corresponds to those of human eyes.



(a)

(b)

Figure 8. Examples of a non-central part of projected images on screen when DMD was illuminated (a) without DOEs and (b) with DOE_1 and DOE_2

DOE_1 was vibrated. DOE_1 with *DS=5* generated 13 beamlets. Theoretical limit for speckle reduction factor of such DOE is $\sqrt{13}=3.6$ [1]. According to our experiment, DOE_1 showed 3.1x speckle reduction factor. Figure 8 illustrates the speckle images without (a) and with (b) DOE_1. When both DOE_1 and DOE_2 were used the speckle reduction factor increased to 4.4.

The effect of blurring of the resulting DMD image border was observed. It can be explained by the following consideration. The image in DMD plane is described by convolution between diffraction orders produced by DOE_1 and DOE_2.

For 1-dimensional case, the energy ratio in uniform intensity part on DMD image is given by

$$Eff_{unif} = \frac{(BS - DS + 1)}{(BS - DS + 1) + (DS - 1)} = 1 - \frac{DS - 1}{BS}$$

In 2-dimensional case, this relation transforms into

$$Eff_{2D-unif} = \left(1 - \frac{DS - 1}{BS_X}\right)\left(1 - \frac{DS - 1}{BS_Y}\right)$$

Experimental measurement results confirm the above relations. The curve in Figure 7(b) demonstrates that the uniform energy efficiency depends on *DS/BS* ratio (see points *64-5*, *64-21*, and *64-41* on this curve). The efficiency decreases with increasing of *DS/BS* ratio.

There is one more DOE design condition to be fulfilled. In our case, the angle of incidence of light on DMD plane has to be less than 6 degrees.

Thus, the DOEs design goal is to approach the following conditions simultaneously:

- Increase *DS* parameter value to improve speckle reduction.
- Decrease *DS/BS* ratio to improve energy efficiency.
- 6° DMD illumination constraint fulfillment.

3. Conclusion and Future Work

We suggested a compact method of DMD illumination using laser as a light source. DOEs perform the functions of laser beam shaper and despeckler. The DOE solution offers more degrees of design freedom than solutions based on lenslet integrators. The flexibility of DOE approach design was demonstrated with two different optical setups for full-color DMD illumination. Experiment results showed that speckle reduction approximately corresponds to the theoretical limit. DOEs with multilevel profiles provide possibility to enhance energy efficiency of lenslet integrators method. The production of designed DOEs can be part of a low-cost mass-fabrication process due to developments in photolithography.

The optical setup described in section 2.2 could be enhanced in the following ways.

1. Remove 0th diffraction order outside DMD area.

The convolution between DOE_1 and DOE_2 improves the uniformity of the central part (which includes 0th diffraction order) of DMD image. However, the more accurate solution to obtain the uniform illumination of the central part is to shift 0th diffraction order outside DMD rectangle. It can be achieved by using off-axis DOE_2. The profile of such DOE should have more than 3 depth levels.

2. Use DOE_1 that generates a non-axi-symmetric illumination.

For example, DOE_1 produces on-axis elliptical illumination. The lengths of minor and major axes of the ellipse match respectively to DS_X and DS_Y diffraction orders. DS_X corresponds to the long side of DMD rectangle (see Figures 6 (b), (c)). In that case it is possible to separately increase the *DS/BS* ratios for *X* and *Y* directions while satisfying the maximum angle of DMD plane illumination constraint.

4. References

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