DMD-BASED RANDOM-ACCESS SCANNER FOR FAST 3D IMAGING AND FABRICATION

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We present a revolutionary way to manipulate and steer ultrafast lasers based on a digital micromirror device (DMD). The DMD scanner performs 3D or random-access scanning, achieving a scanning speed of 22.7 kHz, scanning range of ~103 × 206 × 524 μm^3, and scanning resolution (i.e., minimum step size) of 270 nm and 130 nm in the axial and lateral directions respectively when paired with a 40X objective lens. To demonstrate the performance, the DMD scanner is used to perform 3D two-photon excitation (TPE) imaging on pollen samples as well as two-photon polymerization (TPP) to fabricate 3D structures.

INTRODUCTION

Precise and fast laser beam steering and scanning methods are the foundation of laser scanning microscopes and 3D nano-fabrication systems. Although a variety of high-speed beam scanning methods are available, e.g., resonant galvanometric scanner, polygonal mirrors, and electrically tunable lenses etc., they can only perform fast linear scanning and lack the capability to perform fast scanning among randomly selected points in space, which is critical for both bio-imaging and nano-fabrication. For example, if a scanner can access all points in its work space at equal speed, complex / hollow structures can be fabricated at a much higher build rate compared to the current raster-scanning process used in 3D additive manufacturing systems. To realize 3D random-access scanning using a DMD, we apply the principle of binary holography [1], where each calculated hologram corresponds to a specific point in space. Here, the DMD is used as a programmable binary mask, consisting of several million micromirrors. Each micromirror is an independent pixel with two stable angular positions, i.e., ±12°. For axial scanning, one can program holograms of spherical wavefronts of increasing or decreasing radii to the DMD [2]. For lateral scanning, one can vary the titled phase term with increasing or decreasing periods of fringes [3]. The superposition of the axial and lateral scanning holograms enable 3D random-access scanning [3].

SYSTEM CONFIGURATION

Figure 1 presents the optical configuration of the DMD-based TPP fabrication system as well as TPE imaging system.

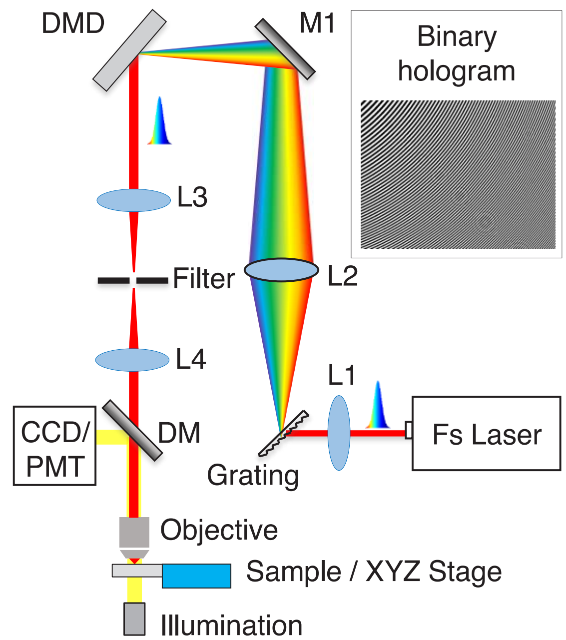

FIGURE 1. Optical configuration of the TPP fabrication system and TPE imaging system, enabled by DMD random-access scanner; M1, M2: high-reflectivity mirrors; DM: dichroic mirror; L1, L2, L3, and L4: lenses

The laser source is a Ti:sapphire femtosecond laser (Chameleon Ultra II, Coherent) with a repetition rate of 80 MHz and an average power of 3.3 W. First, the input laser beam is appropriately expanded to ensure the DMD aperture (DLP 4100 0.7” XGA, 1024 × 768 pixels, Texas Instrument) is fully filled. As the DMD functions both as a programmable binary hologram and a blazed grating, it introduces negative angular dispersion to the laser beam. To remove the angular dispersion, a blazed transmission grating and a mirror (M1) are included in the light path to generate positive angular dispersion [4]. After the DMD, the dispersion-free laser beam is guided to an infinity-corrected objective lens (Nikon CFI S Fluor 40X Oil, NA = 1.3, WD = 0.22 mm) via a 1:1 telescope, consisting of an achromatic lens L3 and a tube lens L4. An iris diaphragm is placed at the back focal plane of L3 to spatially select the -1st order diffraction of the hologram. To observe the fabrication process, a microscopic imaging system is built in conjunction with the fabrication system. As shown in Figure 1, the microscope shares the objective lens with the fabrication setup. A transillumination light source illuminates the translucent sample. The image or video of the sample is then acquired by a CCD camera after the dichroic mirror (DM). The photoresist (IP-Dip, Nanoscribe) is mounted on a motorized precision xyz stage for positioning.

The optical configuration of the TPE microscope is the largely identical to the TPP system. The only difference is that the CCD camera is replaced by a photomultiplier tube (PMT, R10699 and C7950, Hamamatsu), which is synchronized to the DMD trigger signals. A data acquisition card (NI USB-6363, National Instruments) collects and processes the PMT signals to form 3D images. These operations are fully automated by a custom-developed LabVIEW program.

AXIAL & LATERAL SCANNING

Axial scanning along the optical axis (i.e., z-axis) is realized by applying binary holograms of spherical wavefronts of increasing or decreasing focal lengths [2]:

$$\varphi(x,y) = \frac{\pi(x^2+y^2)}{\lambda f} \quad \textbf{(1)}$$

where λ is the wavelength and f is the focal length of the spherical wavefront. Binary holograms of the spherical wavefronts in Eq. (1) is generated based on Lee holography [1]; and can be calculated as

$$h(i,j) = \begin{cases} 1, & -\frac{q}{2} \le \frac{R(x,y)}{T} + \frac{\varphi(x,y)}{2\pi} + k \le \frac{q}{2} \\ 0, & otherwise \end{cases} \quad \textbf{(2)}$$

where $h(i, j) \in \{0, 1\}$, ($1 \le i \le m$; $1 \le j \le n$; $i, j \in$ N) represents the pixels on the DMD; 1 and 0 refer to the "on" and "off" states respectively; m and n refer to the number of rows and columns respectively; T is the grating period of the hologram; k is an integer; and q ($0 \le q \le 1/2$) is a constant that determines the widths of the fringes.

Lateral scanning can be realized by changing the tilted phase term [3], i.e., *R(x,y)/T* in Eq. (2), as *R(x,y)* determines the bias and tilted angle of the fringe patterns and *T* determines the period of the fringes. In other words, *T* may be used to control the separation of diffracted beams from the 0th diffraction order. Figure 2 illustrates the working principle of lateral scanning: To scan the focal point from left (red point) to right (green point), assuming *T* is constant, one only needs to reduce the value of *R(x,y)*. By appropriately selecting the values of *R(x,y)* and *T*, lateral scanning in both *x*- and *y*- axes can be achieved. In combination with the axial scanning, three-axis random-access scanning can be realized by using a single DMD. When selecting design parameters, it is worthwhile to note that a large *T* value may cause the diffracted beams to overlap in space, while a small *T* value may cause the tilted phase term to exceed the range of the inequality in Eq. (2), and thus no modulation will be performed.

As the DMD scanner is capable of scanning arbitrary paths in space, all conventional scanning strategies, e.g., raster, spiral, or Lissajous scanning trajectories, can be easily implemented on the DMD platform. In addition, the dwell time at each point on the scanning path can also be arbitrarily controlled, realizing selective optical stimulation.

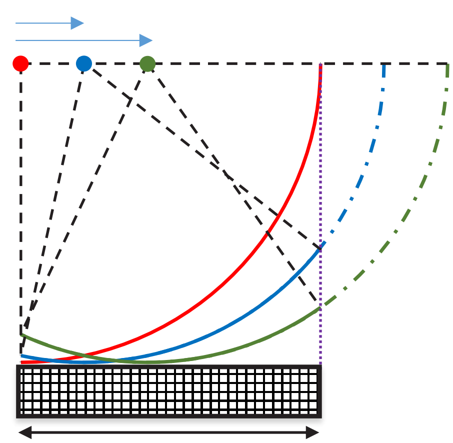

FIGURE 2. Working principle of lateral scanning based on binary holography: The focal point can be scanned from left (red) to right (green) by reducing the value of the tilted phase term, i.e., R(x,y)/T, in Eq. (2), i.e, reducing the value of R(x,y) when T (grating period) is constant.

SCANNING RANGE AND RESOLUTION

The relationship between the scanning performance and the DMD parameters, i.e., pixel size and aperture size, have been studied and reported in [3]. From the parametric model, we can conclude that (1) the lateral scan range is inversely proportional to the DMD pixel size (d) and the magnification of the objective lens(M_{obj}); the axial scan range is inversely proportional to d^2 and M_{obj}^2; and (2) the minimum step size in the lateral direction is inversely proportional to the aperture size (D); the minimum step size in the axial direction is inversely proportional to D^2. Based on the system presented in Fig. 1, the scan range is calculated to be 103 × 206 × 524 μm^3. If a DMD of higher resolution is used, e.g., DLP6500 (d = 7.68 μm), the work volume can be increased by more than a factor of 10. If a low magnification objective lens is used, the work volume can be further increasesed.

Considering the minimum step size, i.e., the smallest variation of binary patterns that will result in a consistent step, assuming the DMD aperture is fully filled by the laser beam, based on the system's DMD model, the lateral/axial minimum step size is calculated to be 0.12/0.27 μm respectively, which is better than typical lateral/axial scanning resolution of TPP fabrication systems, i.e., 0.4/1.4 μm. In other words, our new DMD scanning method, although being entirely discrete and digital, can fabricate continuous structrues with better resolution, and follow arbitrary trajectories in space. Note that the minimum step size can be further reduced by using DMDs of more pixels.

TPP FABRICATION EXPERIMENTS

In conventional TPP systems, the fabrication is performed by a pair of galvanometric scanners that raster-scan the x-y plane. To build 3D structures, a linear stage moves the build plane axially after a layer is completed. This layer-by-layer sequential fabrication process limits the printing speed of complex / hollow structures. Comparing with the conventional method, the total fabrication time of the DMD-based TPP system is only proportional to the total solid volume regardless of the level of complexity. This is because the DMD can randomly access any point in space with equal speed, i.e., 22.7 kHz or 5mm/s, presenting great advantages for fabricating complex structures. In addition, precision laser dose control (i.e., gray scale control) can be achieved by extending the dwell time of the laser focus at any point within the DMD work volume, which cannot be achieved by galvo scanners due to the inertia of mirrors.

To demonstrate the capability of scanning along arbitrary paths, a spiral path with elevating height is designed and illustrated in Fig. 3. Next, holograms of all scan points along the path are generated and loaded to the DMD memory. Note that each point along the path corresponds to a different hologram.

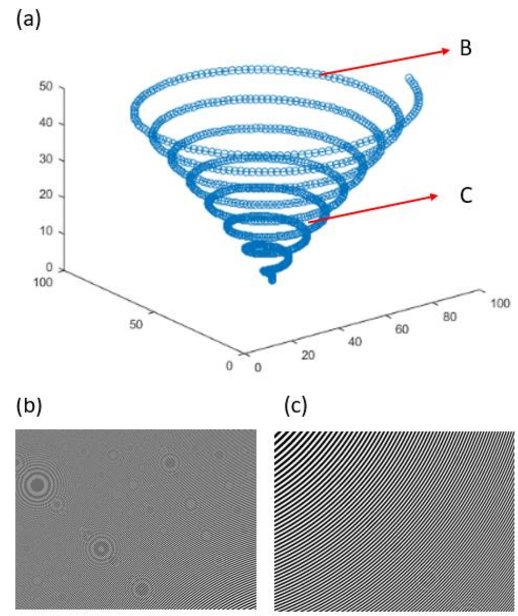

FIGURE 3. Illustration of an arbitrarily generated scanning path for TPP; the holograms of two different points on the scan path (B and C) are shown in Fig. 3B and 3C, respectively.

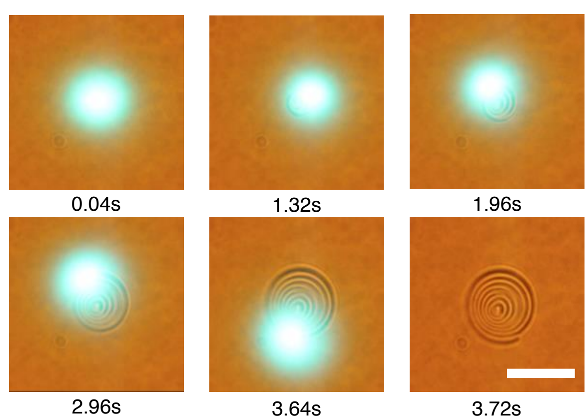

FIGURE 4. Time sequence of the spiral scanning and fabrication process performed by the DMD holography scanner. Scale bar is 25 μm.

Figure 4 presents a time sequence of the fabrication process recorded by a CCD camera, where the focal point precisely scans the planned path, shown in Fig. 3A, and the green emissions confirm the two-photon process. In the experiments, a total of 9,300 holograms are generated to perform the spiral scan; the laser power is set at 10 mW; and the dwell time for each pixel is 400 μs. (Total scanning time is 3,720 ms). Note that the dwell time is purposely set slow for the CCD camera to capture the structure writing process.

Next, we experimentally validate that 3D structures written by the DMD scanner have comparable resolution with conventional raster scanning systems. Figure 5 presents the SEM image of a DMD-scanner fabricated planer grating structure at the DMD's highest pattern rate, i.e., 22.7 kHz. In the experiment, the DMD first fabricates a cubic substrate (20 × 20 μm^2), followed by a grating structure with a target pitch of 1200 nm. In the experiment, 16,000 holograms are generated and used to scan and fabricate the structure. The entire fabrication process is completed within 700 ms, i.e., the pixel dwell time is 44 μs; or the DMD scans at 22.7 kHz. Figure 5B presents a zoom-in view of the grating structure after development, where the linewidth is measured to be 382 nm.

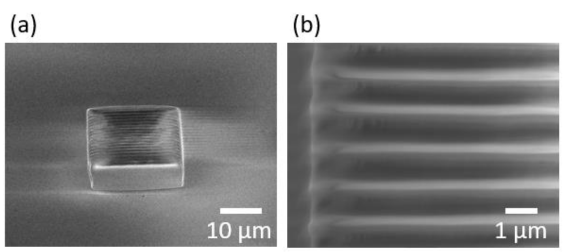

FIGURE 5. DMD Illustration of fabricated structures via TPP: (a) SEM image of printed straight lines with 0.4/1.2 μm linewidth/pitch on a 20 μm X 20 μm cube substrate. (b) Zoomed SEM image of printed straight lines.

TPE IMAGING EXPERIMENTS

By replacing the CCD camera with a PMT, shown in Fig. 1, the TPP fabrication system can be used as a TPE microscope with the unique random-scanning capability. To demonstrate the capability of scanning along arbitrarily defined paths or surfaces in space, the DMD is programmed to scan along spherical and sinusoidal surfaces on pollen samples at 22.7 kHz. Figure 6 presents the imaging results, which show comparable resolution with conventional raster-scanning TPE microscope. In Fig. 6, each optical cross-sectional image contains 100 × 100 pixels, i.e., 10,000 holograms are loaded to the DMD controller for performing this task.

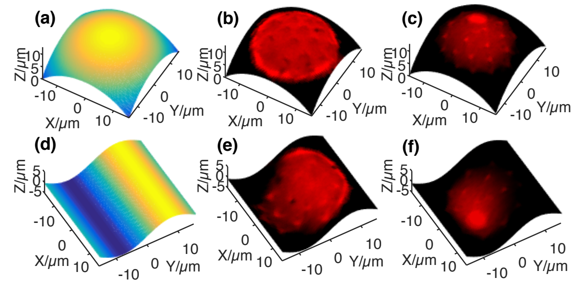

FIGURE 6. Cross-sectional images of two selected pollen grains on arbitrarily programmed spherical and sinusoidal surfaces

CONCLUSION

We present the design of a DMD 3D random-access scanner for applications in TPE imaging and TPP fabrication. In the experiments, we demonstrate the DMD scanner can scan along arbitrarily defined lines and surfaces at the DMD pattern rate, i.e., 22.7 kHz. The new scanning method presents unique advantages in writing complex / hollow structures or imaging scattered points in space, e.g., in vivo neuronal imaging in brains, at high-speed without compromising the fabrication and imaging resolution, which outperforms conventional raster scanning systems. The new method may generate significant impact to the nano-fabrication and biomedical imaging fields.

ACKNOWLEDGMENT

This work is supported by the HKSAR Research Grants Council (RGC), General Research Fund (GRF), (CUHK 439813 & 14202815).

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