Digital Micromirror Device Enabled Angle of Incidence Control for Microsphere Photolithography

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***Abstract*— A Digital Micromirror Device (DMD) at the Fourier plane provides dynamic angular control at the image plane for microsphere photolithography, allowing for a +/-26° angle to be achieved on a microsphere array. A split ring resonator (SRR) on glass has been fabricated for demonstration.**

Keywords—DMD, MPL, AOI control, Fourier mask

I. Introduction

Metasurfaces, with their engineered electromagnetic properties, is a potent material that exhibits significant potential across a broad range of applications [1]. Despite their potential, photolithography and EBL/FIB are expensive and impractical for large-scale fabrication, limiting their use. Alternative techniques such as Nanoimprint lithography (NIL) and Nanosphere lithography (NSL) have their drawbacks, relying on expensive masks or lacking flexibility in patterning [2, 3]. Microsphere photolithography (MPL), which employs subwavelength photonic jets generated by microspheres under plane wave illumination, offers a low-cost, high-throughput alternative [4]. Previous work has demonstrated the ability of MPL for complex geometry by alternating the illumination angle of incidence (AOI) during the exposure process [5]. However, the mechanical movement involved in AOI control leads to complex and time-consuming exposure processes. Bonakdar et al. used a static mask at the front Fourier plane for AOI control [6]. In this paper, we demonstrate the use of a Digital Micromirror Device (DMD) for dynamic and continuous AOI control. A combination of lenses performs a Fourier transform on the DMD and decomposes the light field into plane waves with different propagation angles. We characterize the maximum AOI and patternable area and employ scanning exposure for large-area fabrication. As a demonstration, we fabricate a 1 cm × 1 cm metasurface with SRRs that show polarization-dependent reflection in IR frequencies.

II. Experimental process

A. Optical setup

The experimental setup is schematically illustrated in Fig. 1. A UV lamp (LS-100X-5CP, Bachur & Associates) is used as the light source with λ = 365 nm. A condenser lens (CL) with F = 100 mm focused the light from an engineered diffuser (ED1-C20-MD, Thorlabs) onto the DMD (DLP6500, Texas Instruments) with an AOI of 24°, ensuring the reflected beam is normal to the DMD window. 3 lenses (L1~L3) with F_1 = 60 mm, F_2 = 200 mm, and F_3 = 32 mm are arranged as foci that coincide with each other after the DMD. Here θ is the AOI at the image plane and y is the coordinates on DMD. A square field stop (FS) with W_0 = 8 mm is placed at the back focal plane of L1 to confine the field of view (FOV). The final FOV at the image plane is W = 1 mm. The AOI at the image plane is controlled by the micromirror position on DMD with a maximum value $\theta_{max} = \tan^{-1}((L/2) \cdot F_2/(F_1 \cdot F_3))$. L is the lateral dimension of DMD. An XY translation stage is placed at the final image plane to provide the ability for scanning exposure.

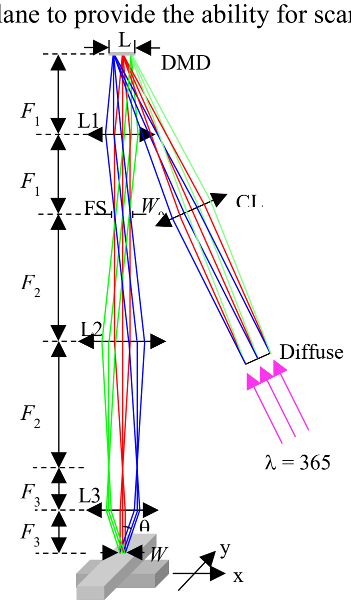

Fig. 1. The schematic illustration of the experiemntal setup

B. MPL process

Figure 2 illustrates the process of fabricating metasurfaces using MPL. First, the positive photoresist (PR) S1805 is thinned by diluting it with PGMEA (Propylene glycol methyl ether acetate, Sigma-Aldrich) at a 2:3 ratio and spin-coated on a glass slide at 5000 rpm/s for 60 s. A microsphere emulsion is then prepared by adding 3 µm dry silica microspheres (Nanomicro) to butanol with an SDS (Sodium dodecyl sulfate) concentration of 30 mg/L. A self-assembled HCP microsphere array is formed at the air/water interface by injecting the emulsion onto the DI water surface and transferring it onto the substrate. The samples are exposed using the setup in Fig. 1 and immediately developed for 30 s in MF 319. Finally, metal is deposited on the substrate

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by liftoff process. FTIR (Thermo Nicolet NEXUS 670) and SEM (Magellan 400) are used to characterize the samples.

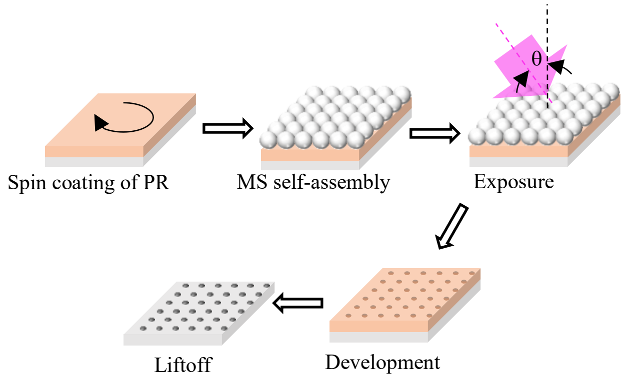

Fig. 2. The MPL process for metasurface fabricaton

III. Results and Discussion

A. Dose curve for scanning exposure

The scanning exposure dose curve is characterized by creating ring patterns on a glass substrate at varying scanning velocities. Two ring patterns, with widths of 100 and 200 pixels, are utilized on a DMD. Fig. 3 displays the relationship between the change in ring width and scanning velocity for each pattern. The inset displays the specific ring pattern used on the DMD. Generally, the width of the ring scales with $1/v$, as slower scanning rates result in longer local exposure durations. Furthermore, a wider ring appears to be more effective in achieving the same feature size at relatively faster scanner speeds. However, a steeper slope is observed for the 200 pixel ring within the range of W from 400 nm to 600 nm because the width of the ring determines the illumination angular distribution on the microsphere, leading to a broadening effect of the photonic jet.

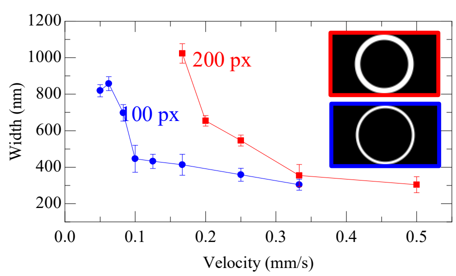

Fig. 3. The dose curve characterized against scanning velocity with different ring width used on DMD

B. SRRs on glass

SRRs, or Split Ring Resonators, were also created on glass and characterized by FTIR. Fig. 4(a) displays the SRRs, which were patterned in a 1 cm × 1 cm area via raster scanning. Fig. 4 (b) shows the SEM image of the SRR resonator with an inset displaying the DMD digital mask. Fig. 4 (c) exhibits the FTIR reflectance spectra that were measured at a 30° AOI under s- and p-polarizations, with the simulation results from HFSS indicated by dashed lines. The stimulated dipole resonance within the SRRs along either the overall or half of the SRR length under orthogonal polarizations shifted the resonant frequencies.

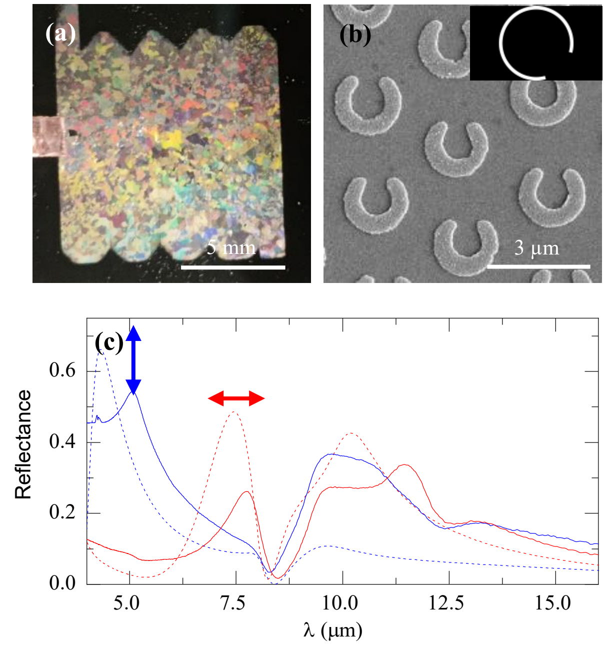

Fig. 4. (a) The SRRs metasurface sample (b) SEM image of (a) with inset showing DMD mask (c) The reflectance spectra udner orhogonal polarizations at 30° AOI from FTIR measurement (solid line) and HFSS simulation (dashed line)

The dynamic angular field control from DMD at the Fourier plane enhanced the flexibility of MPL. With the addition of scanning exposure, the fabrication of metasurface over a 1 cm × 1 cm area with ±26° AOI in all directions has been achieved experimentally. The dose curve has been characterized against scanning velocity and DMD mask size. This method realizes continuously variable AOI control for MPL without any mechanical movement.

References

[1] S. B. Glybovski, S. A. Tretyakov, P. A. Belov, Y. S. Kivshar, and C. R. Simovski, "Metasurfaces: From microwaves to visible," Physics Reports 634, 2016, pp.1–72.

[2] S. Y. Chou, P. R. Krauss, and P. J. Renstrom, "Nanoimprint lithography," Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena 14(6), 1996, pp. 4129–4133.

[3] C. L. Haynes and R. P. Van Duyne, "Nanosphere Lithography: A Versatile Nanofabrication Tool for Studies of Size-Dependent Nanoparticle Optics," J. Phys. Chem. B 105(24), 2001, pp. 5599–5611.

[4] C. Qu and E. C. Kinzel, "Polycrystalline metasurface perfect absorbers fabricated using microsphere photolithography," Opt. Lett., OL 41(15), 2016, pp. 3399–3402.

[5] C. Zhu, C. Qu, and E. C. Kinzel, "Direct-write microsphere photolithography of hierarchical infrared metasurfaces," Appl. Opt., AO 60(24), 2021, pp. 7122–7130.

[6] A. Bonakdar, M. Rezaei, R. L. Brown, V. Fathipour, E. Dexheimer, S. J. Jang, and H. Mohseni, "Deep-UV microsphere projection lithography," Opt. Lett. 40(11), 2015, pp. 2537.