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Printing line/space patterns on nonplanar substrates using a digital micromirror device-based point-array scanning technique

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A R T I C L E I N F O

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Point-array scanning
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A B S T R A C T

This study used a digital micromirror device (DMD) to produce point-array patterns and employed a self-developed optical system to define line-and-space patterns on nonplanar substrates. First, field tracing was employed to analyze the aerial images of the lithographic system, which comprised an optical system and the DMD. Multiobjective particle swarm optimization was then applied to determine the spot overlapping rate used. The objective functions were set to minimize linewidth and maximize image log slope, through which the dose of the exposure agent could be effectively controlled and the quality of the nonplanar lithography could be enhanced. Laser beams with 405-nm wavelength were employed as the light source. Silicon substrates coated with photoresist were placed on a nonplanar translation stage. The DMD was used to produce lithographic patterns, during which the parameters were analyzed and optimized. The optimal delay time-sequence combinations were used to scan images of the patterns. Finally, an exposure linewidth of less than 10 µm was successfully achieved using the nonplanar lithographic process.

1. Introduction

As electronic components have become increasingly advanced, improving the fabrication of nonplanar structures in newer-generation electronic components has attracted increasing attention. How to define layout patterns on nonplanar substrates has emerged as a key issue. Previously, antenna patterns have been defined on integrated circuits using a planar micromirror process; however, this process can only be used on relatively regular and flat substrates. Special polydimethylsiloxane (PDMS) soft mold patterns can be created to transfer and print high-gain antennas, array-type antennas, or radio-frequency identification patterns onto substrates with low curvature [1,2]. Other techniques to solve this problem include using PDMS soft-mold-based pattern transfer printing for the creation of metallic gratings on curved substrates [3,4]; combining nonlinear micromirror and plasma etching techniques to define structural patterns on nonplanar inorganic optical component substrates [5]; and using computer-generated holograms to define 3D patterns on nonplanar substrates [6,7].

Nevertheless, conventional lithography techniques that focus on planar materials still have stable mass-production processes and are widely employed in the manufacture of printed circuit boards (PCBs) for the creation of designed component patterns. Maskless lithography, a laser direct imaging (LDI) technique, is currently used to define circuit patterns with a width of 10–30 µm [8]. Two exposure modes are involved in this technique. The first projects laser beams onto focusing lenses using reflective polygon mirrors as beam splitters. The beams thus produced can be focused on substrates to form lithographic patterns. This technique has large depth of focus (DOF) and high throughput; however, the system is expensive [9]. In response to the market's demand for small-quantity and high-variety patterns, another LDI technique has been developed that employs a digital micromirror device (DMD) as a digital mask. The technique uses a conventional projection-based optical system design that contains microlens arrays (MLAs), thereby enabling beam spot arrays to exhibit more satisfactory resolution regarding the line width. Additionally, this technology is silicon-based and can thus produce DMDs with higher reliability at lower costs than other techniques. As a result, the development of this technology has attracted considerable interest [10].

Multiobjective planning, first proposed by researchers Charnes and Cooper, can be used to solve quality control problems in optical processes [11,12]. Numerous approaches can be used to solve multiobjective problems, including the popular simulated annealing [13] and genetic algorithms [14,15] and also particle swarm optimization (PSO), which has been commonly employed in recent research. The advantage of the PSO algorithm is its global search capability. The concept for the algorithm derived from the foraging behavior of a flock of birds. Each bird in a flock occupies a distinct spatial area and must search for the ideal foraging area. When an optimal foraging spot has been determined

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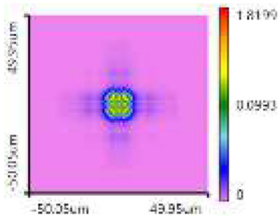
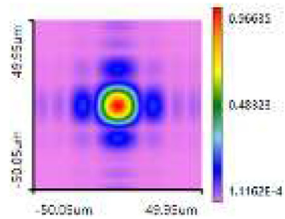
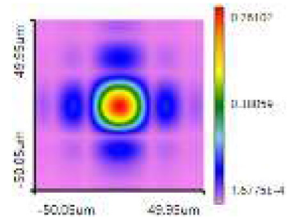
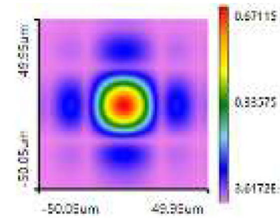
Table 1
Distribution of beam intensity at different distances from the DMD.

Distance (mm)	0	114	142	171
Aerial image (AI)				

locally, each bird flies toward the currently defined optimal spot. Over time, birds tend to flock together to the optimal foraging spot [16].

This study investigated how existing techniques for the definition of layout patterns on nonplanar substrates might be improved using a DMD-based maskless lithography system. The PSO multiobjective algorithm was also integrated to plan the point-array scanning parameters and stage moving velocity. The efficient and highly repetitive LDI technique could then be used to define lithographic patterns on nonplanar substrates.

2. Aerial image analysis

In this study, field tracing (VirtualLab) was used to design the locations of the optical components in the DMD-based scanning lithography system. The locations of the focal lenses in the beam guiding system were first arranged according to the intensity distribution of DMD-deflected laser beams. The incident beam was assumed to consist of linearly polarized plane-waves with a wavelength of 405 nm, and the beam shone on a DMD of diameter 1.3 mm, with the surface area of each mirror in the DMD equal to 13.7 µm × 13.7 µm. Table 1 presents the intensity distribution at different distances from the DMD of light reflected by the device. When the distance was 0 mm, diffraction was observed because of the gaps between micromirrors. As the distance was between 114 and 142 mm, the diffraction side lobe gradually separated from the diffraction main lobe. The first focal lens was placed at a distance of 135 mm from the DMD mirror, and its intensity distribution is presented in Fig. 1(a). To determine the size of the diffraction main lobe, the beam intensity distribution in Fig. 1(a) was crisscrossed into a black line segment. Fig. 1(b) illustrates the beam intensity distribution of this cross section, wherein the beam diameter was approximately 0.3 mm. An aperture was positioned 80 mm behind the first focal lens to eliminate effects of the higher-order side lobes.

The beam continued to propagate after passing through the aperture. The second focal lens was placed 155 mm behind the first. An analysis of the optical field intensity 30, 60, 90, and 120 mm behind the second focal lens was subsequently conducted, and the results are summarized in Table 2. Beams 30, 60, 90, and 120 mm behind the second focal lens that were formulated through focused imaging had a diameter of 480, 40, 240, and 600 µm, respectively. In terms of intensity distribution, the beam formulated 60 mm behind the second focal lens exhibited a more satisfactory beam quality than the beams formulated at other distances, and that beam was most similar to the TEM00 Gaussian beam mode. Therefore, the objective lens was positioned 60 mm behind the second focal lens. The optical beam intensity distribution obtained at various focal positions behind the objective lens was then analyzed, and the results are presented in Table 3. The beam formulated 28 mm behind the objective lens exhibited the smallest spot size, having a diameter of 18 µm. This beam spot characteristic was employed in this study to determine the effect of point-array scanning lithography.

When a nonplanar substrate is exposed, the limited DOF can affect image quality when performing point-array scanning. To effectively control nonplanar lithography quality, this study adopted multiobjective particle swarm optimization (MOPSO) to calculate the optimal lithography parameters. In this technique, particles are first randomly arranged in the solution space (Fig. 2). Each particle knows the position of the optimal solution it has identified so far (P_{ibest}) and the position of the optimal solution currently identified by other particles in the group (P_{gbest}). When a particle needs to move, it integrates the moving velocities at

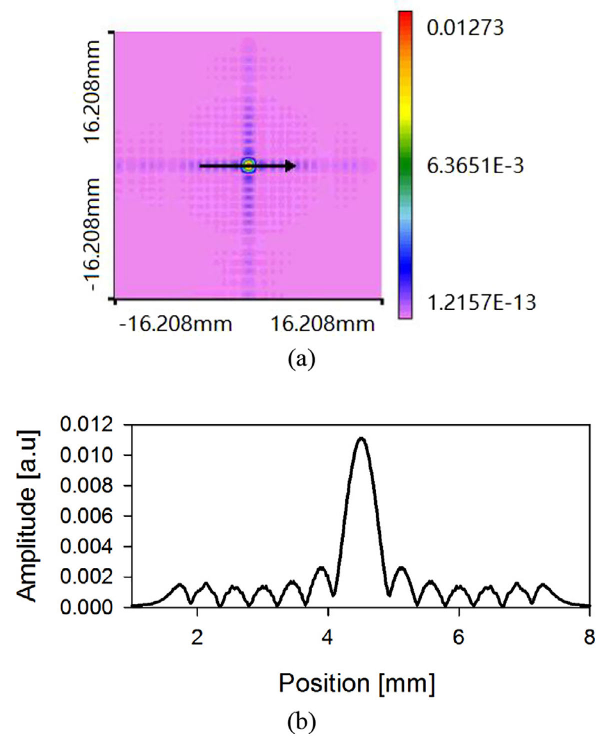


Fig. 1. (a) Distribution of beam intensity 135 mm from the DMD mirror plane; and (b) beam intensity on the crisscrossed black line segment in (a).

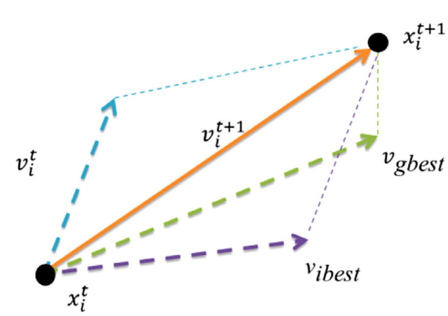


Fig. 2. Mathematical model of particle swarm algorithm.