Addressable microlens array for parallel laser microfabrication

Patrick S. Salter* and Martin J. Booth

Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

**Corresponding author: patrick.salter@eng.ox.ac.uk*

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Parallel processing in femtosecond-laser-based microfabrication is demonstrated using a microlens array in conjunction with a liquid-crystal spatial light modulator (SLM). A portion of the SLM is mapped onto each individual lenslet in the array and can be used to effectively switch foci on and off for fabrication. In addition, the technique allows for homogenizing the intensity of the array of foci and translating spots relative to their natural focus. The technique demonstrates the potential for high efficiency processing of aperiodic structures. © 2011 Optical Society of America

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Direct laser writing is becoming a useful tool in the fabrication of a range of micrometer scale structures. Typically, a femtosecond laser is focused into a suitable substrate, where multiphoton absorption and avalanche effects cause permanent material changes in the focal region [1]. Since the absorption is nonlinear, the modification is highly localized at the focus. Promising applications include the manufacture of waveguides [2], artificial bandgap materials [3], and metallic nanostructures [4]. However, unlike lithographic material processing, the required structures need to be written sequentially, which can lead to long fabrication times. Thus, there is currently great interest in parallel processing techniques, and it has been shown that extended structures can be written simultaneously through the projection of holograms [5–7] or temporal focusing of the pulsed beam [8]. Alternatively it is possible to insert a microlens array into the beam to create multiple foci [9,10]. This technique is well suited to the fabrication of a fixed periodic array of identical structures. However, the method suffers from a lack of flexibility and breaks down if an aperiodic array of distinct structures is required. Furthermore, the fabrication can often be very sensitive to any variation in focal intensity rendering a high degree of uniformity necessary in the beam profile of the laser. In previous work on fiber-optic interconnects [11], it was shown that a liquid-crystal spatial light modulator (SLM) may be coupled to a microlens array in order to address individual lenses simultaneously. We show in this Letter that such a configuration also holds significant potential for flexible parallel microfabrication. Individual foci can be effectively switched on or off for fabrication and steered from their natural focus, allowing for the fabrication of aperiodic structures. In addition, the intensity of individual spots can be adjusted and aberrations compensated, enabling a high degree of uniformity across the array.

Figure 1 shows a schematic of the experimental setup. The pulses emitted from the regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, 100 fs pulse duration, 1 kHz repetition rate, 790 nm center wavelength) were attenuated using a rotatable half-wave plate and a Glan-Taylor polarizer. The expanded beam was directed onto a reflective liquid-crystal phase-only SLM (X10468-02, Hamamatsu Photonics). The SLM and the microlens array were mapped together by a $4f$ imaging system, which was composed of two achromatic doublet lenses with focal lengths 300 mm and 250 mm. The microlens array (SUSS MicroOptics) comprised 18×18 square plano-convex lenslets with a pitch of 500 μm and focal length 15.5 mm. The array of foci was demagnified by a microscope comprising a 200 mm achromatic doublet tube lens and a 50× Leitz objective with a numerical aperture of 0.85. The specimen was located on a three-dimensional (3D) piezo stage (Tritor 102 SG, Piezosystem Jena) which provided up to 80 μm translation in all axes. The system incorporated an LED-illuminated transmission microscope for observing the specimen. The plane of the microlens array was conjugate to the SLM so that when the former was imaged onto the CCD, the boundary of each microlens could be seen relative to switched pixels on the SLM, as demonstrated by the inset of Fig. 1. Thus, by observing the switched area on the CCD, one could determine the appropriate active region of the SLM (30 pixels × 30 pixels) necessary to control the focus corresponding to a single microlens.

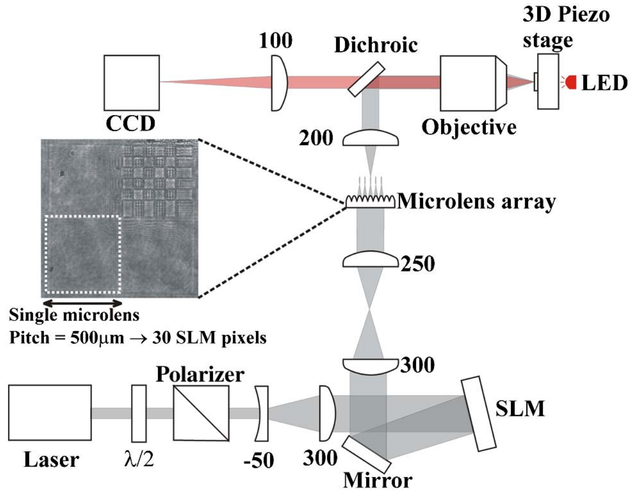

Fig. 1. (Color online) Experimental setup for addressable multispot micromachining. The inset shows an image of a 2×2 segment of the microlens array mapped onto the SLM (a binary phase checkerboard is applied to the region of the SLM corresponding to the top right lenslet).

The SLM only modulates the phase profile of the incident beam, but individual lenses could still be disabled for fabrication without the inclusion of additional polarizing elements by taking advantage of the strong threshold phenomenon in short pulsed ablation [1]. If the intensity is below a certain material-dependent threshold, too few photons will be absorbed to create a plasma appreciable enough for structural modification. In the focal plane of the objective, the pulse energy may be spread to a level below this fabrication threshold through the application of an appropriate phase pattern to the SLM. Here, we utilize a binary phase checkerboard applied to the active region of the SLM conjugate to the lens to be switched off. The period of the checkerboard was 12 pixels ($240\,\mu$m) and each diffractive order was sufficiently shifted from the zeroth-order and low enough in intensity to preclude fabrication. The diffraction efficiency for the SLM with a grating of this period is ~70%, such that there was a significant zeroth-order, but this was also below the threshold for fabrication. Figure 2(a) demonstrates the principle. A mirror was inserted in the specimen plane to reimage the focal array onto the CCD camera, while several lenses have been activated for fabrication to display the text "OXF." For the deactivated foci, four clear diffraction orders, in addition to the zero order, are visible. Each is lower in intensity than the unaffected foci by a factor greater than four, and by appropriate adjustment of the beam intensity one can obtain fabrication only with light from the activated lenses. Figure 2(b) shows the result when the same pattern is incident on the surface of a slab of fused silica. A burst of 50 pulses, each with energy $10\,\mu$J, was applied. Voids of ablated material can be seen where the lenses are activated, while there is no fabrication where the lenses are switched off.

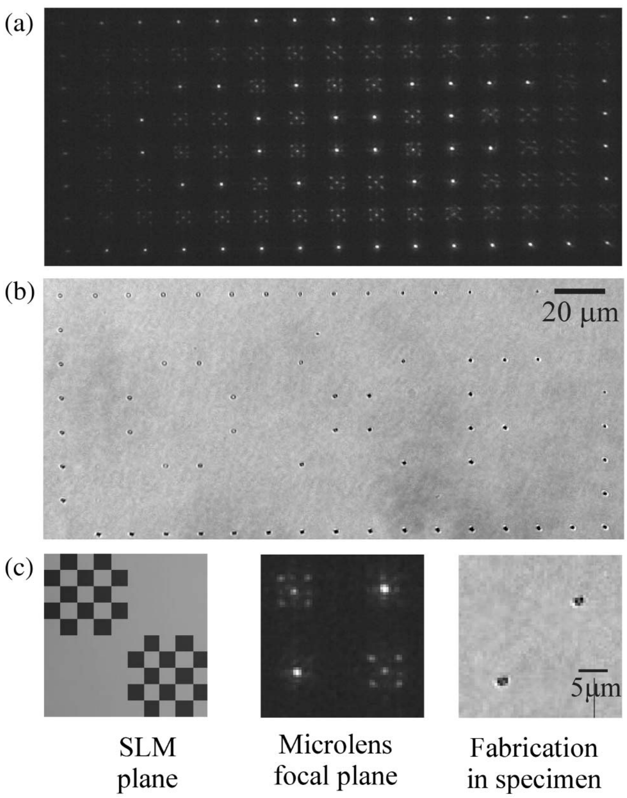

Fig. 2. (a) Intensity distribution at the focus of the objective, where several microlenses in the array have been deactivated for fabrication through spatially spreading the incident pulse energy at the focus. (b) Resultant fabricated array of voids on the surface of a fused silica slab. (c) Images of a 2×2 section of the system, showing the phase pattern applied to the SLM, the subsequent intensity distribution in the focal plane of the objective, and the associated ablation of fused silica.

Because of the nonlinear nature of the absorption process, there can be significant problems for fabrication if there is any nonuniformity in the spot intensity across the array. This is typically related to the intensity profile of the illumination across the lenslet array [9] and is difficult to correct for. However, the SLM coupled to the microlens array can be used to homogenize the intensity of all the intended fabrication spots. Furthermore, an appropriate phase pattern applied to the SLM can correct for small amounts of aberration in each lens and add a defocus element to guarantee all the spots lie in the same focal plane. The intensity of individual spots was controlled in the following manner. The intensity at the focus is proportional to $|\sum_n e^{i\phi_n}|^2$, where ϕ_n is the phase of the nth pixel and the summation is carried out over all SLM pixels imaged onto the pupil of the microlens under consideration. The intensity of a particular focus is reduced by introducing a π phase shift to a randomly selected pixel within the pupil. If the proportion of changed pixels is small, then the shape of the light field is predominantly unaffected. Figure 3(a) shows a portion of the SLM conjugate to a single lenslet in the array with a flat wavefront corresponding to maximum focal intensity, while in Fig. 3(b), a number of pixels have had their phase reversed to reduce the focal intensity by 10%. Experimentally, a greater number of pixels must be flipped than might be expected due to the inability of the SLM to produce sharp phase steps between adjacent pixels. Figure 3(c) displays the initial intensity distribution (observed on the CCD camera using a mirror specimen in the focal plane of the objective), while Fig. 3(d) displays the intensity distribution after the homogenization process. The standard deviation in the intensity of the array of spots dropped from 0.21 to 0.1. The improvement in the uniformity of fabrication can be seen in Figs. 3(e) and 3(f). Both images show voids ablated from the surface of a fused silica slab after a burst of 50 $25\,\mu$J pulses, without [Fig.3(e)] and with [Fig.3(f)] homogenization of the focal array.

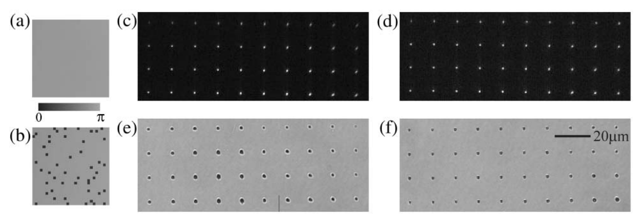

Fig. 3. Active region of the SLM corresponding to a single microlens with a flat phase profile and (a) a π phase shift introduced to a random selection of pixels to reduce the focal intensity by 10%. (b) Images of the array of foci before and (c) after (d) the homogenization process. The resultant fabrication is seen on the surface of fused silica without and (e) with (f) homogenization of the microlens array.

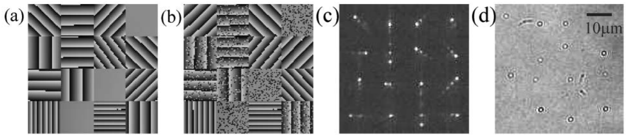

Fig. 4. Phase pattern applied to the SLM to variably steer individual lenslet foci and create a 4×4 aperiodic array of foci, before and (a) after, (b) taking into account the SLM beam steering inefficiency. The associated focal intensity distribution and surface ablation are shown in (c) and (d), respectively.

The ability to switch individual lenses on or off allows the fabrication of an aperiodic array of features. In addition, each spot can be steered from its natural focus. A linear phase gradient applied to the SLM translates the focus transverse to the optic axis, whereas a quadratic phase profile introduces defocus. This raises the possibility that spots could be steered to cover any point in a volume below the focal array. However, due to the imperfect reproduction of the phase pattern by the SLM, there is a considerable decrease in intensity as the focus is directed to greater angles. In order to direct a focus to the edge of its particular unit cell, a phase gradient of 19π radians is required across the associated region of the SLM (30 pixels). The SLM has a maximum modulation depth of 2π when illuminated by light of wavelength 790 nm, and thus there is a phase wrap every ~ 3 pixels. The phase gradient at the phase wrap is naturally not infinite so the desired phase pattern is in effect smoothed out, and the intensity of the steered focus decreases with the increasing number of wraps across the pupil of the lens. To counter this, we decreased the intensity of the unperturbed foci by randomly flipping the phase of a proportion of pixels across the pupil of the corresponding lens by π. As the amount of beam steering distance away from the natural focus increased, the proportion of flipped pixels was reduced to maintain a uniform intensity. The SLM phase pattern shown in Fig. 4(a) is suitable for the generation of a 4×4 aperiodic array of foci, while the effect of the beam steering inefficiency is compensated in the phase pattern in Fig. 4(b). The intensity distribution in the focal plane created by the phase pattern in Fig. 4(b) is shown in Fig. 4(c), where the increase in the zeroth-order may be clearly seen for foci shifted further from their unperturbed position. The associated ablation from the surface of a fused silica slab is shown in Fig. 4(d). The fabrication was realized with a train of 50 16 μJ pulses of energy.

To conclude, we have demonstrated a fully addressable microlens array for use in laser-based microfabrication. A liquid-crystal SLM coupled to the microlens array is used to independently control individual spots. In particular, spots may be selectively deactivated for fabrication through the application of a suitable phase pattern to spread the energy distribution in the focal plane of the lens to a level below the fabrication threshold. This leads to the potential for an "inkjet" style of printing in microfabrication. Furthermore, the appropriate phase applied to the SLM can correct for imperfections in the optical system and homogenize the intensity of the array of foci. In addition, individual foci are steered from their natural focus using suitable phase gradients, and we show in principle that it is possible to cover the entire area within the array for fabrication.

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