High-quality generation of a multispot pattern using a spatial light modulator with adaptive feedback

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We propose and demonstrate high-quality generation of a uniform multispot pattern (MSP) by using a spatial light modulator with adaptive feedback. The method iteratively updates a computer generated hologram (CGH) using correction coefficients to improve the intensity distribution of the generated MSP in the optical system. Thanks to a simple method of determining the correction coefficients, the computational cost for optimizing the CGH is low, while maintaining high uniformity of the generated MSP. We demonstrate the generation of a 28×28 square-aligned MSP with high uniformity. Additionally, the proposed method could generate an MSP with a gradually varying intensity profile, as well as a uniform MSP consisting of more than 1000 spots arranged in an arbitrary pattern.

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An important issue in laser processing and microscopy is enhancing the throughput, e.g., the processing rate and scanning speed. One way of solving this problem is to perform simultaneous processing or measurement with a multispot pattern (MSP). MSPs have been applied to laser processing [1], fluorescence correlation spectroscopy [2], and optical manipulation [3,4], where MSPs are generated with computer generated holograms (CGHs) displayed on spatial light modulators (SLMs). One problem, however, is that the intensity distribution of light spots in the MSP is nonuniform. Several numerical studies [4–6] have examined how the uniformity of an MSP is affected by the CGH design algorithm. In the previous studies [4,7,8], the MSP uniformity is deteriorated by extrinsic factors in a practical optical system, such as distortion of the wavefront, tilting of lenses, finite-size effects of pixels in the SLM, and crosstalk between pixels. Some reports have discussed the methods for generating uniform MSPs in optical systems [8–12], but further improvement will be necessary for developing practical laser processing and microscopy.

In this Letter we propose and demonstrate the high-quality generation of a large MSP. The present method involves iteratively updating a CGH using correction coefficients to improve the intensity distribution of the MSP in an optical system. Thanks to a simple method of determining the correction coefficients, the computational cost for optimizing the CGH is low, while maintaining high uniformity of the generated MSP. Using the present method, we generated a 28×28 square-aligned MSP with improved uniformity, as well as a 10×10 square-aligned MSP with an varying intensity distribution and a highly uniform MSP consisting of 1442 points arranged in an arbitrary pattern.

Figure 1 shows the basic principle of the present CGH updating scheme for generating a MSP consisting of M spots. The position of the mth spot is denoted as (x_m, y_m) in a signal space [5] and sometimes expressed as (m) for simplicity in the following. The CGH is designed through a two-stage iterative procedure: one is an "outer" iteration that determines correction coefficients for improving the uniformity of the MSP observed in a practical optical system and the other is an "inner" iteration for designing a CGH with the correction coefficients. The outer iteration is performed as follows. First, the MSP is generated using a CGH determined in the previous inner iteration. Then, we observe the intensity distribution of the generated MSP, $I^{(k)}(m)$ for the mth spot [(k) indicates the repetition of the outer iteration], using a CMOS image sensor and evaluate the uniformity of MSP as a standard deviation of $I^{(k)}(m)$ with respect to the spot number m. If the uniformity is insufficient, the correction coefficient $v^{(k)}(m)$ is modified as

$$v^{(k)}(m) = v^{(k-1)}(m)\sqrt{I^{(k)}(m)/I^{(k-1)}(m)}, \tag{1}$$

using $v^{(k-1)}(m)$ and $I^{(k-1)}(m)$ given in the previous [$(k-1)$th] outer iteration, except for $v^{(0)}(m) = 1$ and $I^{(0)}(m) = 1$. The calculated $v^{(k)}(m)$ is then incorporated into inner iteration to update the CGH, which is applied for generating the MSP in the next outer iteration. Implementation of the inner iteration is based on overcompensation (OC) method [5,6], a kind of weighted

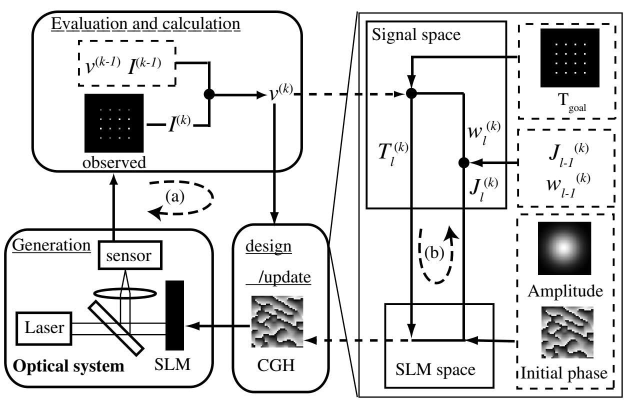

Fig. 1. Block diagram of the proposed method: (a) outer iteration and (b) inner iteration. Parameters in dashed boxes are stored in memory.

error-reduction algorithm, but differs in using the correction coefficient $v^{(k)}(m)$ determined in the kth outer iteration to compensate for actual experimental effects. At the lth inner iteration, the intensity distribution $T_l^{(k)}(m)$ in the signal space is updated as [5,6]

$$T_l^{(k)}(m) = v^{(k)}(m) w_l^{(k)}(m) T_{\mathrm{goal}}(m), \tag{2}$$

with respect to a desired intensity distribution $T_{\mathrm{goal}}(m)$. In Eq. (2), $w_l^{(k)}(m)$ is a conventional OC-weight parameter that is determined via a similar relation to Eq. (1). In the conventional OC [5], the weight parameter is updated according to the calculated intensity distribution $J_l^{(k)}(m)$ derived by successive operation of Fourier and inverse Fourier transformations to $T_l^{(k)}(m)$; i.e., $w_l^{(k)}(m)$ is updated by the relation of Eq. (1) with replacing the roles of v and I to those of w and J, respectively [$w_0^{(k)}(m)$ and $J_0^{(k)}(m)$ are chosen as unity]. When $T_l^{(k)}(m)$ becomes sufficiently closed to $T_{\mathrm{goal}}(m)$, an inverse Fourier transformation of $T_l^{(k)}(m)$ gives the CGH pattern for the next outer and inner iterations, and the inner iteration is finished with storing $w_l^{(k)}(m)$ and $J_l^{(k)}(m)$ for the $(k+1)$th iteration.

Experiments were performed using a similar optical setup to that in [4]. A horizontally polarized light emitted from a laser ($\lambda = 532$ nm) was mode cleaned through a spatial filter and modified to a top-hat beam by a lens and a 7 mm diameter aperture. The top-hat light was projected onto a liquid-crystal-on-silicon spatial light modulator (LCOS SLM; X10468-01, Hamamatsu) [13,14] The SLM modulated the phase of the incident light and reflected it. The first-order diffraction components was reflected by a half mirror and focused onto a CMOS image sensor (ORCA-Flash 2.8, Hamamatsu) by a convex lens ($f = 250$ mm).

We designed a CGH for generating a 28×28 square-aligned MSP, in which each spot was separated by a distance of four times the Airy disk. The CGH was composed of 600×600 pixels, each of which achieved phase modulation ranging from 0 to 2π [rad.] by 180 discrete steps of phase gradation. Here, a pattern for compensating for the wavefront distortion caused by SLM and optics was superimposed on the CGH [14] Additionally, a Fresnel lens pattern ($f = 1000$ mm) was also superimposed to shift focal position of MSP from the undesired zeroth-order diffraction component.

Figures 2(a) and 2(b) show observed MSPs generated with the present method and with the conventional OC method, respectively. Owing to the additional Fresnel lens pattern, the undesired zeroth-order diffraction component vanishes in Fig. 2(a). Here, the size of Airy disk were 43.6 ± 1.49 μm in the present condition and the averaged distance between spots was 177.9 μm in Fig. 2(b), leading that each spot in MSP was separated by a distance of 4.1 times the Airy disk.

In Fig. 2(b), two types of nonuniformity, which are caused by extrinsic factors in the optical system, are clearly observed. One of them is a shading effect; i.e., the spot intensities in the peripheral area are reduced compared to those in the central area and the other is an irregular intensity fluctuation. To examine the uniformity of the MSP, we focused attention on the spot intensity distribution. The spot intensity distribution was evaluated by root mean square (RMS) and peak-to-valley (PV) measurements. RMS and PV, denoted as σ and η, respectively, can be expressed as

$$\sigma = \sum_{m=1}^{M} \sqrt{[I(m) - I_{\mathrm{desired}}]^2 / M}, \tag{3}$$

$$\eta = (I_{\max} - I_{\min}) / (2 I_{\mathrm{desired}}), \tag{4}$$

where $I(m)$ is the sum of intensities in a region-of-interest (ROI) around the mth spot, while $I_{\max}$, $I_{\min}$, and I_{desired} are the maximum, minimum, and desired values of $I(m)$, respectively. Here, the ROI was chosen as a 12×12 pixel area on the CMOS image sensor around the center of gravity of each spot. Figure 2(c) shows the changes of η and σ as the adaptive feedback process proceeded. After the thirtieth outer iteration, we achieved a highly uniform MSP whose η and σ were 0.037 and 0.010, respectively, whereas η and σ for the conventional OC method were 0.54 and 0.12. Moreover, we investigated the diffraction efficiency of the present MSP. Diffraction efficiency was evaluated as a sum of the spot intensities divided by an intensity of the zeroth-order diffraction light from an uniform phase pattern displayed on the SLM. The diffraction efficiency is marked 0.40 after

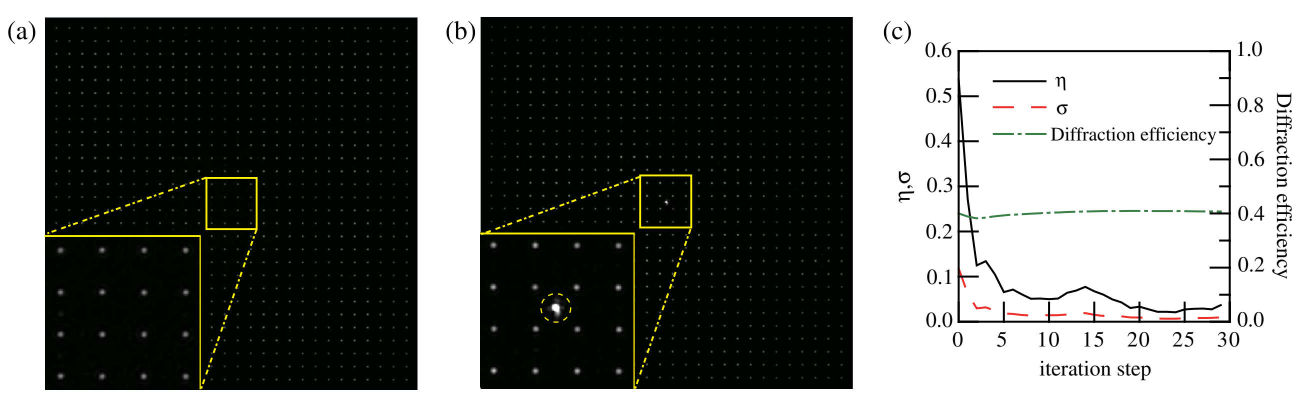

Fig. 2. (Color online) Observed 28×28 square-aligned MSP obtained by applying (a) the present method and (b) the conventional OC method. (c) Relation between the number of adaptive feedback iterations and the diffraction efficiency.

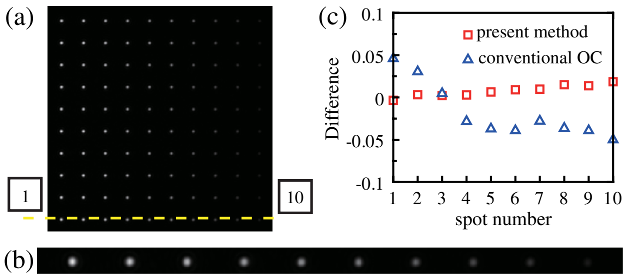

Fig. 3. (Color online) (a) 10×10 square-aligned MSP whose intensity distribution varies in the row direction, (b) magnified view, and (c) differences between the designed and measured spot intensities along the dashed line in (a).

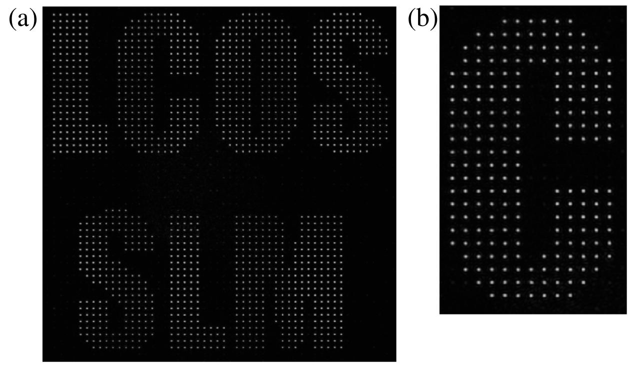

Fig. 4. (a) Observed characters “LCOS SLM” composed of 1442 points and (b) magnified view around character “C.”

the thirtieth outer iteration, the result of which is similar to that for the conventional OC method (0.41). The diffraction efficiency of the present result is lower than [6] because our texture of CGH is more complicated for generating a larger number of spots. We examined the MSP fidelity in terms of the displacement, size, and peak intensity of the spots via fitting analysis to a Gaussian profile. In this analysis, we assumed that the generated spots were aligned on a uniformly spaced square grid. The standard deviation of the displacement was ± 2.4 μm in the column direction and ± 2.7 μm in the row direction, both of which are smaller than the pixel size of the CMOS image sensor (3.63 μm). The standard deviations of the spot size and relative peak intensity were ± 1.78 μm and ± 0.028, respectively.

So far, we have been concerned with the generation of a uniform MSP, but it is also possible to generate an MSP with an arbitrary intensity distribution and an arbitrarily aligned spots. We can generate an MSP with an arbitrary intensity distribution by introducing a variable amplitude in the target pattern $T_{\mathrm{goal}}(m)$. Figure 3(a) shows a 10×10 square-aligned MSP whose intensity distribution varies according to the direction as $I_{\mathrm{row}} = 1 - 0.09 \times (\mathrm{row} - 1)$. Figures 3(b) and 3(c) shows magnified view, and differences between the designed and measured spot intensities along the dashed line in Fig. 3(a). In Fig. 3(b), η is improved from 0.11 to 0.02 and σ is improved from 0.023 to 0.010. We also demonstrated the generation of an MSP with arbitrarily aligned spots. Figures 4(a) and 4(b) show the observed result of characters “LCOS SLM,” formed by 1442 points. In Fig. 4, η and σ were 0.027 and 0.010, respectively, with the present method, compared with 0.44 and 0.11 for the conventional OC method.

We have described the generation of a high-quality MSP. Various MSPs can be adaptively generated by using an SLM to reconstruct CGH. Our proposed method takes less than 180 s for 30 outer iterations using a personal computer with Intel core i7-3820, where most of the time is assumed to design a CGH. The proposed method will be useful for high-accuracy laser processing, and observation of specific positions in microscopy.

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