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| *Original published in:* | EOS Annual Meeting (EOSAM 2022) : Porto, Portugal, September 12-16, 2022. - (2022), art. 13013, 2 pp.<br>(The European physical journal : Web of Conferences, Vol. 266) |
| *Conference:* | European Optical Society Annual Meeting (Porto, 12.-16.09.2022) |
| *DOI:* | https://doi.org/**10.1051/epjconf/202226613013** |
| *Original published:* | 2022-10-13 |
| [*Visited:* | 2023-11-28 ] |

EPJ Web of Conferences **266**, 13013 (2022) https://doi.org/10.1051/epjconf/202226613013
*EOSAM 2022*

# Micro-diffractive optical element arrays for beam shaping

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**Abstract.** We describe the design of Fourier type array generators and beam shapers as periodic configurations of refractive-diffractive optical elements in microscale to provide specific beam shaping and imaging functionalities. We investigate how the addition of micro-nanostructures to regular microstructure arrays enables new degrees of freedom for the design of micro-optical systems, in combination with adapted fabrication techniques yields a better optical performance and leads to enhancement of the array concept, uniformity and efficiency.

## 1 Introduction

Microlens arrays (MLA) as one of the most well-known microstructured arrays, are arrangements of microlenses on a single substrate. One of the most prominent applications is in beam shaping and generation of arrays of equidistant and uniform intensity peaks referred to array illuminators, which is based on aperture division [1] . The growth of the fields of applications of the microstructure arrays, is connected to the complexity of the corresponding optical structure and the advancement of the fabrication techniques.

New fabrication technologies pave the way for combining different complex diffractive and refractive structures on a single micro-optical element, which enables new degrees of freedom. In this contribution we investigate a method for enhancement of the array generators and the evolution of application areas by addition of diffractive microstructures to regular MLAs. We use analytic and numerical design and optimization methods to design micro structured micro-lens arrays and study their achievable functionalities. we propose a new fabrication sequence for the complex structure of the optimized array with standard regular MLAs as starting point for the fabrication. In this concept, we suggest to fabricate the diffractive microstructures with reduced requirements on the spatial complexity, on regular MLAs. We will further investigate the system advantages, tolerances and limitations as a result of lithographic fabrication of microstructures on the curved surfaces of refractive MLAs.

## 2 Design of array illuminators

Uniform laser-beam irradiation is needed e.g. for laser microfabrication, laser welding and multi-location, parallel and simultaneous processing but is increasingly also interesting in imaging applications such as light sheet microscopy [2] . An efficient method for designing the phase distribution for beam shaping applications is based on the iterative Fourier transform algorithms (IFTA), suggested by Gerchberg and Saxton. This optimization algorithm, allows the design of a DOE generating a specific diffraction pattern for a given illumination pattern. The algorithm can be started with a random phase function or an appropriate starting phase distribution.Based on this principle, modifications have been suggested e.g. by Fienup with the aim to increase efficiency and uniformity [3].

Here, we investigate the design and fabrication of array illuminators, based on Fienup algorithm and MLAs. Due to the periodicity of the MLA it is possible to regard it as diffraction gratings. Therefore, based on the theory of diffraction, the intensity pattern of the modulated beam is defined by an amplitude modulation due to the interference of the beams from individual microlenses. The beam shaping ability in array generators is achieved by replacing a conventional MLA by a micro-structured diffractive optical element array, in which individual diffractive optical elements is optimized to generate any given diffraction pattern. One advantage of the method is that a poor uniformity in the input beam does not affect the generated spot array uniformity. However, there is a limitation due to the complexity of the diffractive structure. The larger the number of output spots or the desired output intensity pattern, the larger the complexity of the diffractive structure. The uniformity in the spots is determined mainly by the fabrication precision. It is affected more severely if the complexity of the diffractive micro-structure is very high.

As the MLA itself generates a signal spot array with poor uniformity, we employ it as the initial guess for the subsequent optimization procedure. In our case, the basic period of the transmission function of MLA as the array generator, defines the pattern and the intensity distribution of the desired signal spots [4]. The fundamental period of the 2D pattern generator, which is a single square-framed microlens is given by:

$$t(x, y) = exp[i\phi(x, y)]rect(\frac{x}{d})rect(\frac{y}{d}) \qquad (1)$$

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Where d is the spatial period and the microlens phase expression, $\phi(x, y)$ is defined by:

$$\phi(x, y) = \frac{-N\pi(x^2 + y^2)}{d^2} = -\frac{\pi(x^2 + y^2)}{f\lambda} \qquad (2)$$

The 2D pattern generator concentrates most of the diffracted light into the desired signal pattern of $N \times N$ spots. However, it does not provide satisfactory uniformity among the generated spots. The modulation profile generated by the MLA is the far field diffraction pattern, determined by the discrete Fourier transform (DFT) of the phase modulation.

In order to design a beam shaper array generator we replace the MLA by a micro-diffractive optical element (mDOE) array in which the individual diffractive structure is optimized to generate a given diffraction pattern with uniform intensity distribution. The phase profile is designed and optimized using the iterative error reduction Fienup algorithm with a starting phase distribution of a MLA to generate $N \times N$ spots. We defined the ideal phase modulation to provide a signal spot array with perfect uniformity and optimum efficiency, as a signal constraint during the optimization process. Fig. 1. Shows the starting MLA phase and the optimized mDOE array with the corresponding 2D signal spot array of $N = 17$.

Fig. 2 shows the single period of the optimized mDOE

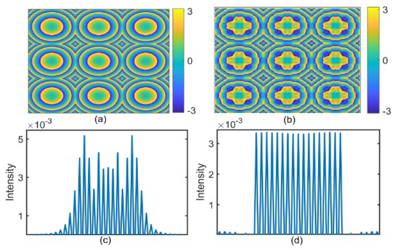


**Figure 1.** Starting MLA (a), optimized mDOE array phase structure of a $17 \times 17$ spot array generator (b), intensity distribution of the spot arrays generated by MLA (c) and mDOE array (d).

and the unwrapped subtracted structure of the mDOE from the single microlens and the corresponding unwrapped phase profiles of the elements. By subtracting the diffractive microstructures of the mDOE from the starting MLA phase, it is possible to fabricate the additional microstructure (STR), as the result of optimization process, on the curved surface of the conventional MLA, as the starting phase. Combining different complex diffractive and refractive structures on a single micro-optical element allows us to fabricate more complex structures, which in turn provides more complex functionality.

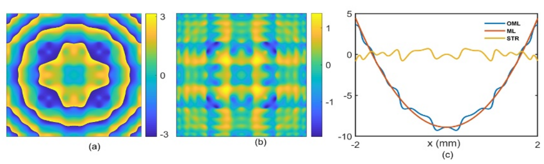


**Figure 2.** (a) Single period of the optimized mDOE array. (b) Single period of the subtracted structure of the mDOE from the microlens, (c) profiles of the phase structures at single periods of

We simulated the performance of the STR structure quantized into 8 phase levels, etched onto the curved surface of the MLA and the effects of possible alignment errors in the lateral directions. The simulation results show a good uniformity among the array spots.

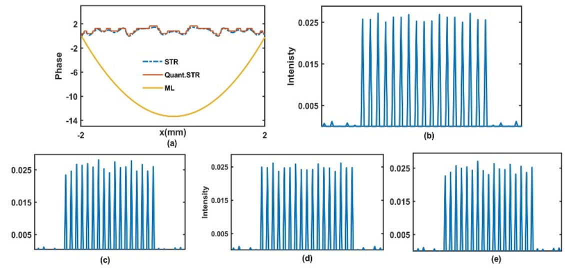


**Figure 3.** (a) Single periods of the quantized STR and the microlens. (b) Intensity distribution of the signal spots, (c-e) Intensity distribution of the signal spots for alignment error of 1μm in lateral x, y and both x and y directions .

## 3 Summary

In summary, we investigate a method for enhancement of the array generators and beam shapers by addition of diffractive micro-nanostructures to regular MLAs as the classical array generators. As a result, we propose a new fabrication sequence for the complex structure of the optimized mDOE which uses standard regular MLAs as starting point for the fabrication. In this concept, we suggest to fabricate the diffractive microstructures with reduced requirements on the spatial complexity on regular MLAs, e.g. by imprint lithography [5].

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