Refractive Micro-optics for Multi-spot and Multi-line Generation

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Multi-spot optics are applied for process parallelizing if the demand on throughput in mass production rises or large areas of material have to be processed. We investigate the usage of microlens arrays as multifunctional elements for forming an arbitrary shaped laser beam into a spot-, a ring-spot- or a line-array pattern. It can be shown that the intensity distribution of each spot is equal to the intensity distribution of all other spots in the whole pattern. We demonstrate that besides other optical properties the output beam profile strongly depends on the Fresnel-Number and is influenced by diffraction and interference effects. We present important design rules which consider geometrical and physical optics. The properties of the spot arrays, like spot diameter, Rayleigh length and beam divergence in dependency of beam and system properties are investigated. Finally we will show some laser micro structuring and micro drilling results in different materials.

Keywords: Micro-optics, array generator, dot matrix, laser line, microlens, homogenizer

1. Introduction

Innovative laser technology allows a continual improvement of production efficiency with the intention of cost reduction in modern manufacturing technology, especially in mass production. On the one hand the ongoing development of new laser sources with a continual increase of laser power approves higher production speeds for example in the application of hole drilling or perforation but is still limited by the mechanical properties of positioning systems. On the other side the quality of laser machining depends on laser properties like laser power or pulse duration.

Parallelizing a laser process can increase the throughput of the production. This can be done with a so called array generator, an optical systems that splits a light beam in a 1 - or 2-dimensional array of beamlets [1, 10]. In the 80s array generators were regarded as one of the key components for optical computers. They were proposed for uniform illumination of a 16x16 matrix of optical switches with a light source. Today, in the field of laser materials processing, optical measuring technology, biotechnology and medicine many new applications for efficient array generators can be found. A number of optical systems and elements have been developed for generation of multiple focus or spot arrays for applications like drilling, perforating, surface texturing, micro- and nanofabrication [2] or skin treatment [3].

In this paper we show the usage of a spot array generator in a so called fly's eye setup consisting of two identical microlens arrays. We present the principle setup and demonstrate the application for micro-structuring and multi hole drilling.

1.1 Single microlens array as spot generator

A very simple method to generate a spot matrix is the illumination of a micro lens array with a collimated laser beam. The location (x_n, y_m) and the intensities I_n, of the individual focal points in the array will be determined by the wavefront properties and the intensity distribution of the incident laser light. Illumination of the microlens array with a plane wave results in a regular dot matrix. Deviations of the wavefront will lead to a lateral shift of the focus points. This allows a high-resolution measurements of the wavefront within Shack-Hartmann sensors. [4]. If the microlens array is illuminated with a Gaussian intensity profile, the intensity of the individual points of light in the spot array strongly decreases to the outside (Figure 1). Due to inhomogeneous (Gaussian) envelope of the spot pattern, a single microlens array is only of very limited usage as an array generator. For generating an envelope function with a flat-top intensity distribution typically two microlens arrays in a fly's eye condenser setup are used.

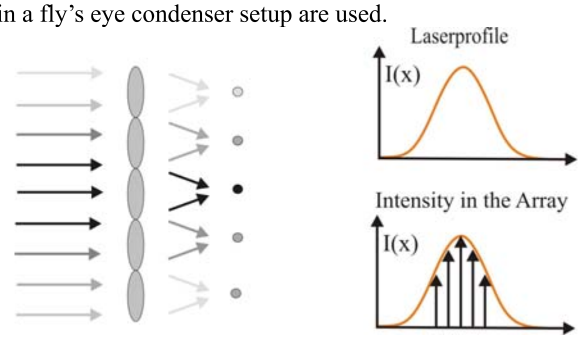

Fig. 1 Illuminating a lens array with a collimated and coherent Gaussian laser beam

1.2 Fly's eye condenser

For over a hundred years Köhler integrators or fly's eye condensers (figures 2 and 3) were used for the homogenization in lighting systems [5]. The classical fly's eye condenser consists of two identical microlens arrays at a distance of the focal length of the microlens array (MLA) and a fourier lens FL (positive lens). The first microlens array (MLA1) splits the incident laser beam into beamlets (aperture division). The microlenses of the second array (MLA2) act as field lenses and project the entrance pupil of the first arrays to infinity. In the focal point of the Fourier-lens FP all images of the entrance pupils are superimposed. By using a fly's eye condenser the light in the target plane is mixed and homogenized. Regardless of the beam profile of the incident light a homogeneous flat-top profile (figure 2) can be generated [6, 7, 11].

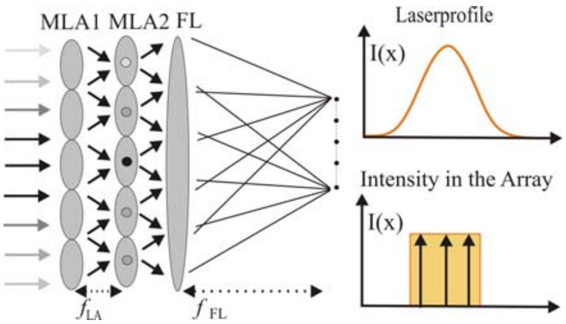

Fig. 2 Fly's eye condenser for flat-top generation

2. Basics of fly's eye spot array generators

When illuminating a fly's eye condenser with collimated and coherent laser beam, a strong light intensity modulation of the flat-top can be observed. This modulation is caused by interference of light of the several channels in fly's eye condenser.

2.1 General description of spot array generator

A regular microlens array is a periodic structure with a period p_{LA} showing effects like grating inference and Talbot self-imaging [8]. The first microlens array devides the incident beam and generates spots on the 2nd array. Light interacting with a periodic structure will always keep traces of this periodicity in its further propagation. This is well explained by Fourier optics: The Fourier transformation of a comb function is again a comb function. This remaining periodicity usually generates a modulation in the target plane, a matrix of discrete spots is observed. Thus, the splitting of the beam itself introduces the modulation of the flat-top intensity. Obviously, the influence of these effects depends strongly on the coherence of the light source.

Using microlens arrays in a fly's eye setup as shown in Figure 2 and illuminating the setup with a coherent and well collimated laser beam, results in a the flat-top intensity profile that is subdivided into sharp peaks. Due to the finite extension of the microlens array the peaks will not be sharp delta functions, but the comb function will be convoluted with the Fourier transform of the aperture function of the illuminated part of the microlens array.

For homogenizing a coherent light source with the help of a fly's eye condenser, these interference phenomena are obviously undesirable. For using a fly's eye condenser anyhow, it is necessary to fill the subapertures of the second microlens array. This can be done by increasing the divergence of incident laser beam or by appropriate choice of the laser source [9]. Typically the beam propagation factor M^2 is ideally larger than 10.

The envelope function of the dot matrix is defined by the shape of subapertures of the first microlens array (MLA1). For square microlenses with a quadratic aperture a matrix of square dots is observed. Square microlenses with a filling factor of almost 100% are best choice, because they allow almost lossless transformation of the incident light into a dot matrix with a homogeneous envelope.

2.2 Important design rules and equations

A scheme of a fly's eye array generator is shown in figure 3.

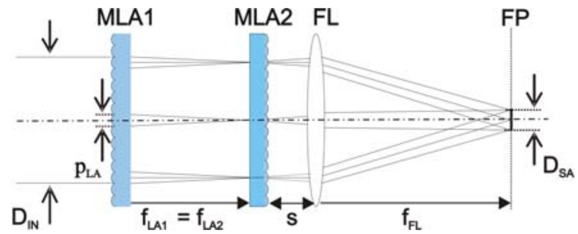

Fig. 3 Fly's eye array generator. Two microlens arrays MLA1 and MLA2, one spherical Fourier lens FL.

The Fresnel number is an important measure to characterize the influence of diffraction effects onto the single lens of the microlens array. The Fresnel number describes the number of Fresnel zones of a spherical wave which is formed by a lens with a diameter D_{lens} (we assume that $p_{LA} = D_{lens}$ for a filling factor of 100% of the microlens array) for an incident plane wave with wavelength λ.
The number of points N formed by a fly's eye array generator correlates with the Fresnel number of the lenses within the 1st MLA [7]:

$$N = 4 \cdot FN = \frac{p_{LA}^{\;2}}{\lambda \cdot f_{MLA1}}, \qquad (1)$$

with p_{LA} the pitch of the lens array, the focal length f_{LA} and wavelength λ. For a circular diameter $Ø_{FL}$ of the illuminated aperture of Fourier lens FL each spot is of course an Airy disc with a radius r_{Airy} between the central peak and the first minimum of:

$$r_{Airy} = 1.22 \frac{\lambda \cdot f_{FL}}{Ø_{FL}}. \qquad (2)$$

A periodic microlens array will behave like a diffraction grating and will generate diffraction orders with a period Λ_{FP} in the target plane FP

$$\Lambda_{FP} = \frac{\lambda \cdot f_{FL}}{p_{LA}}. \qquad (3)$$

To show the correlation between the element properties within the homogenizer and the output beam dimensions of the envelope function we used the paraxial matrix method for a first approximation of the geometrical optic. For our analysis we assume a point source at infinity illuminating the first lens array MLA1. The size of the envelope of the spot-matrix D_{FT} depends on the focal lengths of the lenses within the array and the Fourier lens and is given by

$$D_{FT} = p_{LA} \frac{f_{FL}}{f_{LA2}}. \qquad (4)$$

For fly's eye spot array generator the divergence θ (half angle) of the envelope of the spots is given by

$$\tan\theta \quad = \frac{1}{2}\cdot\left(\frac{D_{IN} - 2\cdot p_{LA} + D_{FT}}{f_{FL}} + \frac{p_{LA}}{f_{FL}}\right), \qquad (5)$$

where D_{IN} is the diameter of the incident beam and s the distance between the second lens array and the Fourier lens. In this equation we assume that the separation *s* between the second lens array and the Fourier lens is zero. Normally the divergence increases slightly by increasing this separation.

2.3 Talbot effects at spot array generator

Already in the 19th century William Henry Fox Talbot explained the Talbot effect as a phenomenon of self-projection of periodic structures. When lighting a periodic structure with a plane monochromatic wave identical images of the original structure are generated after a distance of a so-called Talbot-length $z_T = 2p_{LA}^2 / \lambda$. Therefore the periodic structure generated by a microlens array is repeated to one Talbot length respectively.

An interesting phenomenon that is relevant for the application of array generator are fractional Talbot images [8] which are formed by illuminating an array generator with monochromatic and coherent light. After a distance of $z = ¼\cdot z_T$ behind the original spot matrix a double number of points can be found. In general we can say that the coherent illumination of a periodic optical element generates periodical structures in each plane behind the optical element. The Talbot effect occurs in most types of array generators and allows to increase the working distance or to work with a greater number of spots in specific fractional Talbot levels.

3. Experimental results

3.1 Generation of spot arrays in a square matrix

For our first investigations we illuminate a fly's eye spot array generator with a collimated laser beam generated by a HeNe-Laser at a wavelength of 632 nm and a collimated beam diameter of 3.6 mm. For our first experiments we use 2 microlens arrays in the fly's eye setup on a monolithic substrate. These monolithic components are based on miniaturized cylindrical lens arrays on front and backside of the substrate fused silica. For generating a spot matrix with a quadratic envelope function, the two elements, each with cylindrical structures are crossed by an angle of 90 degrees.

The pitch of the microlenses is 250 µm and the focal length of a single lens is approximately 1.6 mm at the selected wavelength. We use a plan-convex fourier lens with a focal length of 100 mm. Figure 4 shows experimental results of a fly's eye spot array generator. A spot matrix with approximately 60 x 60 spots, a spot diameter of 22 µm and a pitch of 250 µm is generated. The envelope of the spot array is a flat top with a measured homogeneity (standard deviation) better than 2 %.

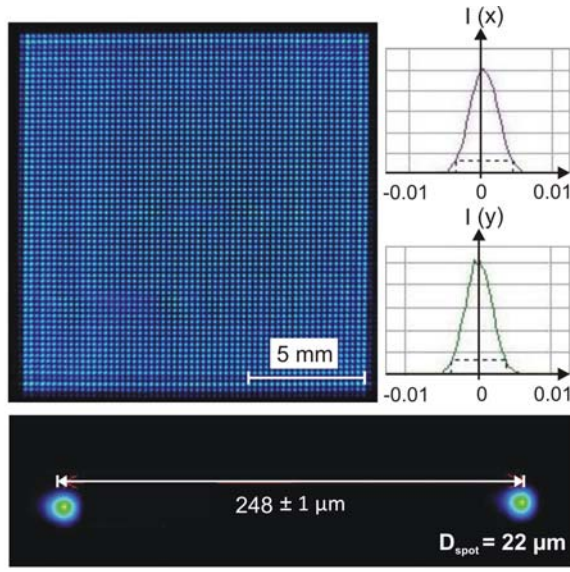

Fig. 4 Spot-Array generated with fly's eye setup

Another important laser parameter in the field of material processing is the propagation of the beam diameter, especially the Rayleigh length of the single beamlets after focusing. We investigate the influence of different diameters of the raw beam on the spot diameter. Figure 5 shows the propagation of a single beam in the spot array in dependence of the incident beam diameter. The Rayleigh length of the beamlets is between 650 µm and 1 mm depending on the beam diameter at the fourier lens.

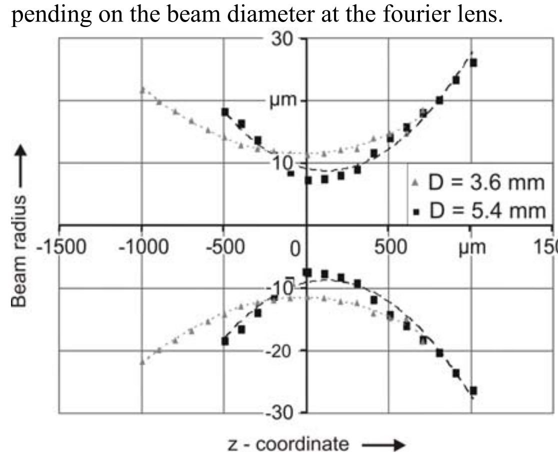

Fig. 5 Measured beam caustics for different collimated beam-diameters

3.2 Generation of ring spot arrays and line arrays

According to Streibl [1] each spot corresponds to the Fourier transformation of the light source, typically a laser beam. By shaping the angular spectrum of the incoming beam the spot shape and size can be influenced. The lower the divergence of the source the sharper is the spot. Due to chromatic aberration the spot size is also influenced by the spectral bandwidth of the source, but in most laser applications this effect could be neglected. Fig. 6 (left figure) shows the resulting spot array of a collimated laser beam which illuminates an axicon right before it enters the beam homogenizer. The axicon generates a beam with an annular angular spectrum. In the Fourier plane of the spot array generator an array of separated circles is observed. The sizes of these circles correspond to the angular spectrum of the light in front of the homogenizer. By using a cylindrical lens in combination with a cylindrical fly's eye spot array generator multiple lines can be created. An example of line arrays is shown in figure 6, right image. As it was already demonstrated above, the envelope function of the pattern is also a flat-top. The uniformity of this envelope is better than 2%.

Illuminating a microlens beam homogenizer with light coming out of a multi-mode fiber will generate a similar pattern of spots. However, these spots are shaped by the actual mode profile at exit of the multi-mode fiber.

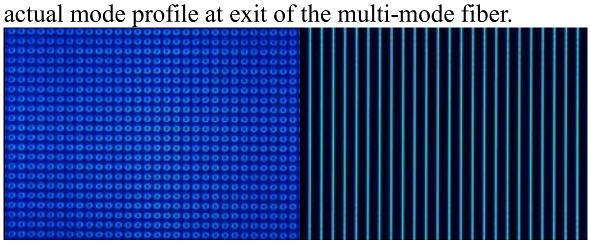

Fig. 6 left: Array of ring spots generated by usage of axicon, right: multiple lines generated by usage of cylindrical setup

The previous experiment demonstrated the correlation of the beam divergence of the incident laser beam and the resulting pattern. For spot array generators used for micro structuring, a plane wave illumination is preferred to obtain sharp spots.

3.3 Micro structuring of silicon

For the micro structuring experiments we used a pico-second laser (Lumera, Staccato) with a pulse width of 10 ps, average power of 2 W, M^2 of 1.5, raw beam diameter of 1.5 mm and a wavelength of 532 nm. The laser operates at 33 kHz repetition rate. Furthermore 2 identical microlens arrays in the fly's eye configuration with a pitch of 300 µm and a focal length of 18.8 mm (@532 nm) were used. The aperture of each microlens within the array has a quadratic structure, therefore the MLA is also called square-microlens array. The focal length of the Fourier lens (planar-convex, BK7) is 100 mm. The resulting Fresnel number of the setup is 2.25 so we expect a matrix of 9x9 laser spots with a spacing of approximately 175 µm and a diameter of a single spot of 35 µm. For our investigations a silicon wafer with a thickness of 550 µm was used. Due to the square shape of the microlens aperture the envelope function of the spot array also has a square contour.

Figure 7 shows a microscope image of a microstructured silicon surface. The left figure shows an example where the sample was moved by a linear stage, therefore a grid is generated. The distance measured between the lines is approximately 179 µm ±5 µm and the width of the lines 46 µm ± 5 µm. The dimensions of the ablation results are close to the theoretical values. The microscope image in figure 7 right, shows single spots generated by the same spot array generator.

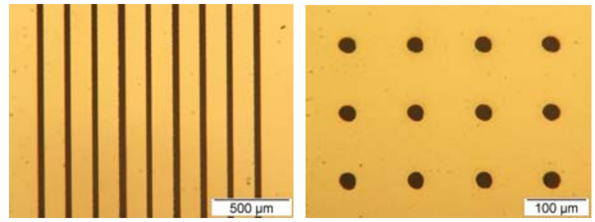

Fig. 7 Microscopy image of the ablated silicon surface. a) Lines generated be moving the sample relative to the spot array, b) single shot

3.4 Foil Perforation with CO2 Laser

Spot array generators can be used for perforating plastic foils in packaging industry, especially for food wrapping. Important in this application beside the high throughput is the generation of highly precise, small holes with a determined clearance. The benefit of the micro-perforation of packages is the extension of the due date of fresh foods because of the better climate inside the package. The permeability of humidity is blocked, the water repellent effect on the surface of the package remains and at the same time the exchange of fresh air is warranted. For rip open assistance in plastic packages a multiplicity of spot along a line are used for a determined attenuation of the mechanical supporting foil. This leads to a decrease of the required force and allows a defined ripping of the packaging. Due to the excellent absorption in plastic material generally CO_2-Laser with wavelength between 9.4 µm and 11 µm are used for these applications.

The number of spots, the single spot size and the clearance depends on microlens and laser properties. In general a larger wavelength leads to a smaller number of spots with an increasing of the spot diameter in the same way. For the investigations a single-mode CO_2-laser with a wavelength of 10.6 µm and a beam diameter of 9 mm was used. The spot array generator consists of two identical silicon microlens arrays in a fly's eye setup and a zinc selenide Fourier-lens with a focal length of 50 mm. The pitch of the square type microlens arrays is 1015 µm with an angle of divergence of ±1.5°. With the given equations the clearance between the matrix of 3 x 3 spots is approximately 0.5 mm and the diameter of a single hole approximately 100 µm. Figure 8 shows examples of a spot array in a plastic foil (material PTFE – Polytetrafluorethylen) with a thickness of 25 µm. The melt-ring around the hole is desired and avoids the ripping of the foil if stress is applied to the material.

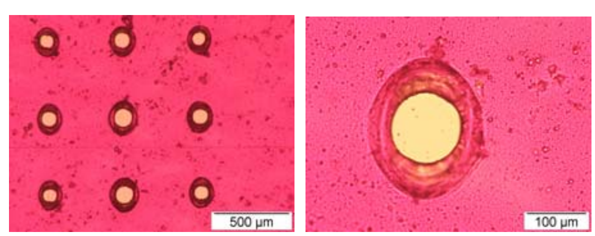

Fig. 8 Spot array in plastic-foil (material PTFE - Polytetrafluorethylen) with a thickness of 25 µm

4. Conclusion

We explained capabilities of microlens arrays for generating patterns like annular, line or Gaussian spot arrays. The envelope of the structures is homogeneous. Design rules which consider geometrical and physical optics were presented. We demonstrated a simple estimation of diffraction influence and we observe a good agreement between theoretical values and experimental results. Examples of the usage of microlens beam homogenizer in CO_2-laser perforation and microstructuring of silicon were shown.

References

[1] Streibl, N.: “Beam shaping with optical array generators,” Journal of Modern Optics, Vol 36, No. 12, p. 1559-1573 (1989).

[2] Keller, G. S.: “Fractional ablative skin resurfacing with the pixel laser.” http://www.almalasers.com, (12/2007).

[3] Kato, J.; Takeyasu, N.; Adachi, Y.; Sun, H.; Kawata, S.: “Multiple-spot parallel processing for laser micronanofabrication,” In: Applied physics letters 86, (2005).

[4] Pfund, J., Beyerlein, M.: “Shack-Hartmann sensors for quality control in classical and laser optics,” photonics 4, p. 6-8 (2002).

[5] Räntsch, K., Bertele, L., Sauer, H. and Merz, A.: “Illuminating System,” US-Patent 2186123, United States Patent Office,(1940).

[6] Zimmermann, M. et al.: “Microlens laser beam homogenizer: From Theory to Application,” Proceedings of Optics and Photonics, San Diego, USA, 2007.

[7] Harder, I., Lano, M., Lindlein, N. and Schwider, J.: “Homogenization and beam shaping with microlens arrays,” Photon Management, Proceedings of SPIE, 5456, 99-107 (2004).

[8] Besold, B. and Lindlein, N. “Fractional Talbot effect for periodic microlens arrays,” Optical Engineering 36 (4), 1099-1105 (1997).

[9] Bich, A. et al.: “Multifunctional Micro-Optical Elements for Laser Beam Homogenizing and Beam Shaping,” Proceedings of LASE2008, Photonics West, San Jose, USA, (2008).

[10] Streibl, N., Nölscher, U., Jahns, J., Walker, P.: “Array generation with lenslet arrays”, Appl. Options, Vol 30, No. 19), p. 2739-2742 (1991)

[11] Dickey, Fred M. and Holswade, Scott C.: “Laser Beam Shaping,” Theory and Techniques, Publisher: Marcel Dekker, (2000).