Laser Beam Homogenizing: Limitations and Constraints

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ABSTRACT

Laser beam homogenizing and beam shaping are key enabling technologies for many applications today. Periodic microlens arrays are widely used to transform Gaussian or non-uniform beam profile into a uniform "flat-top". Each microlens element samples the input beam and spreads it over a given angular distribution. Incoherent beams that are either temporally or spatially incoherent can produce very uniform intensity profiles. However, coherent beams will experience interference effects in the recombination of the beams generated by each individual microlens element. Rotating or moving elements, such as a rotating diffuser or a vibrating optical fiber, are used to average these interference patterns. An integration of several different patterns will smooth out the intensity profile. Unfortunately, this averaging is not always possible. Some applications require a single shot from a pulse laser or work at very high data rates that do not allow an averaging over 10 to 50 frames. We will discuss the concepts of Köhler illumination and Köhler integrators and its limitations and constrains for laser beam homogenizing. We will show how micro-optical elements comprised of a randomly varying component can be used to smooth out interference and speckle effects within the far-field intensity profile.

Keywords: Köhler integrator, fly's eye condenser, laser beam homogenizer, micro-optics, microlens arrays, beam shaping, laser beam shaping, laser material processing, random diffusers

1. INTRODUCTION

Illumination concepts from microscopy have been successfully applied to modern laser technology. The homogenization of laser beams is an important issue not only in many fields of laser material processing, but also in laser measuring techniques and analysis. Most of all, those laser applications, which image a mask pattern onto a work piece, require a homogenous distribution of radiation intensity over the whole mask area and consequently over the whole machining plane. Other applications require a homogenous thin laser line; only one beam direction is homogenized. Various elements and optical systems have been developed for laser beam shaping. Hoffnagle et al. [1] described a refractive beam shaper which can be used to sort the light into a flat-top distribution using two specially designed aspherical lenses. The disadvantages of such systems are the strict dependence on the entrance profile and the proper alignment. Alignment errors and fluctuations of the laser beam have a strong influence on the achieved uniformity. Beam shaping with diffractive optical elements represents a very elegant and powerful method for the generation of arbitrary irradiation patterns [2]. These elements are usually designed for a specific wavelength and phase function. To achieve high performance, i.e. beam uniformity and efficiency, multi-level elements are necessary. Another concept for flat-top generation uses multi-aperture elements, which divide the incoming beam into a number of beamlets. The beamlets are overlapped with the help of an additional lens. The advantages of these shapers are the independence from entrance intensity profile and wide spectrum of wavelengths. However, the periodic structure and the overlapping of beamlets produce interference effects especially with the usage of highly coherent light. Nevertheless a successful homogenization with these elements can be achieved with the consideration of physical optics [3] and in certain cases with the usage of additional elements like random diffusers.

2. THE KÖHLER ILLUMINATION CONCEPT

In 1893, August Köhler of the Carl Zeiss corporation introduced a new and revolutionary method for uniform illumination of specimen in an optical microscope [4]. The Köhler method allows adjusting the size and the numerical aperture of the object illumination in a microscope independent from each other. The Köhler illumination system consists of two lenses and two diaphragms. The following conditions apply:

A. The collector lens images the light source to the plane of the aperture diaphragm.
B. The aperture diaphragm is located in the front focal plane of the condenser lens. Each point in the aperture diaphragm is imaged to infinity.
C. The field diaphragm is imaged to the target plane by properly adjusting the distance from the condenser lens to the object plane.

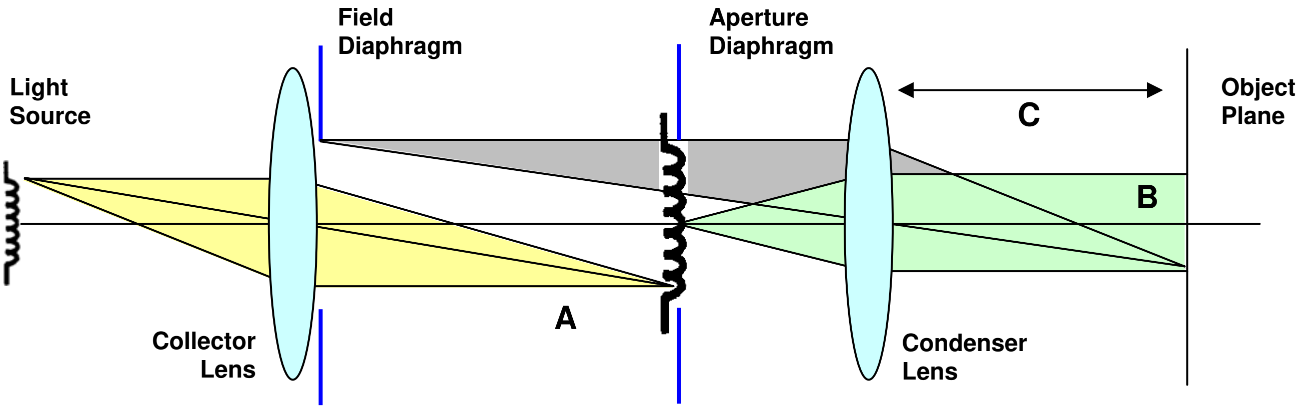


Figure 1. Principle of Köhler Illumination using light from a light bulb to illuminate an object plane

Köhler illumination provides uniform illumination of the object plane independent of shape, extension and angular field of the light source. Köhler illumination decouples the object illumination from the light source. Each source point can be treated as generating a coherent, linearly polarized plane wave of spatial frequency determined by the position of the source point relative to the optical axis. Köhler illumination was a major milestone in the history of optical microscopy and is still widely used today. Köhler illumination is also the basic principle behind laser beam homogenizing.

2.1 The Köhler Integrator

Further improvement of illumination is achieved by using a Köhler integrator as shown in Figure 2. A Köhler integrator consists of two lens arrays and a condenser lens forming side-by-side multiple Köhler illumination systems [5]. A first lens array LA_1 divides the incident light and generates multiple images of the light sources in the aperture plane. The first lens array LA_1 also serves as an array of field diaphragms defining the illuminated area in the object plane.

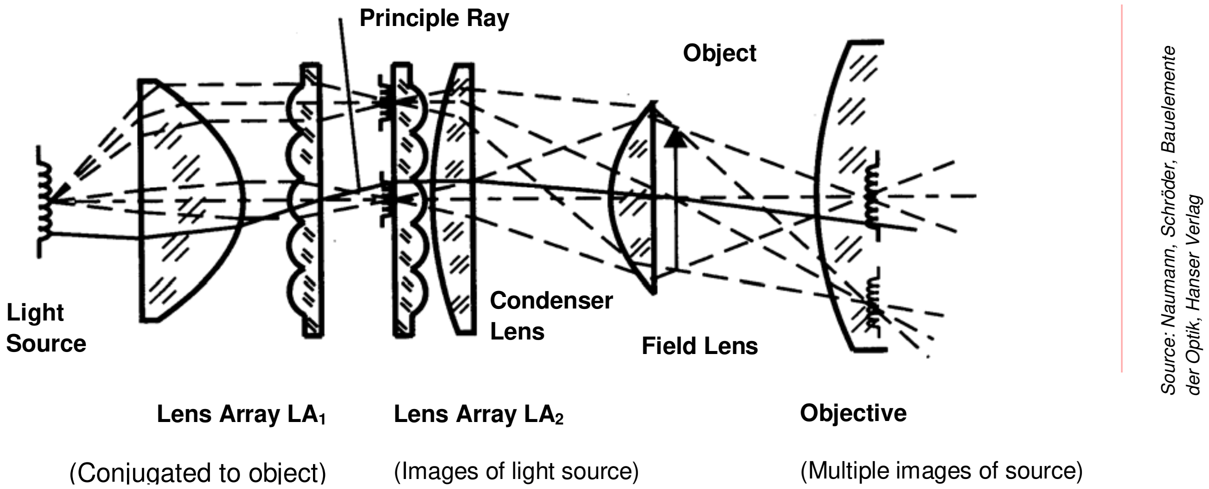


Figure 2. Köhler Integrator for slide projection. Two lens arrays and a condenser transform light from a lamp filament for uniform illumination of a transparent object. The object is imaged by the objective lens.

A second lens array LA_2 is located in the aperture plane and serves as an array of aperture diaphragms. The lenses of the second array LA_2 and the condenser lens image the individual field diaphragms to the object plane. Sharp images of the filament appear in the pupil plane of the objective lens. This ensures a uniform illumination of both the object and the image plane. In the object plane, real images of the sub-apertures of the first lens array LA_2 superpose as shown in Figure 3. Assuming that the light irradiance is approximately uniform over each sub-aperture of LA_1 or that the incident light irradiance is symmetric, the superposition of all images provides a uniform intensity distribution in the object plane. Typically arrays of 10x10 microlenses are sufficient to achieve good flat-top uniformity.

Example: Gaussian intensity distribution at lens array LA_1

Simulation of superposition in object plane for two identical microlens arrays consisting of NxN identical lenses.

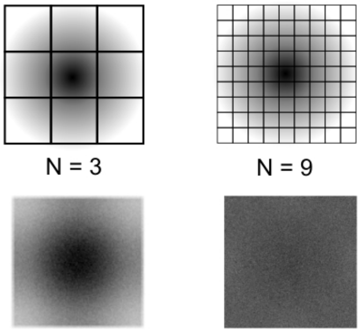
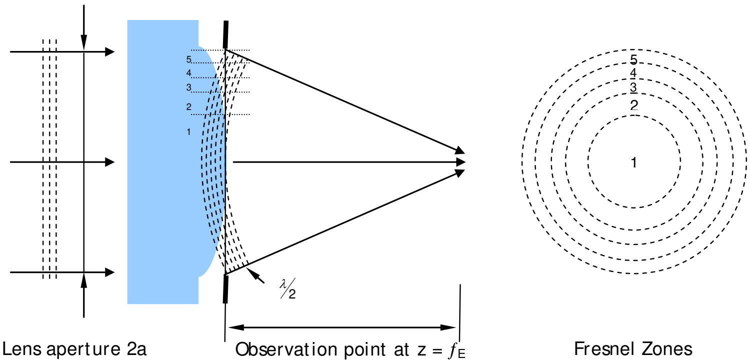


Figure 3. Illustration of the intensity redistribution in the object plane in dependence on the number of lenses N

As shown above, increasing of the number of lenses will improve the quality of the homogeneous intensity distribution. However, if the lenses are getting too small, diffraction effects will significantly distort the flat-top uniformity. As shown in Figure 2, the basic mechanics of a Köhler integrator is the imaging of the first array's sub-apertures by the corresponding lenses of the second array. The quality of the superposed images of these sub-apertures strongly influences the flat-top uniformity. Consequently, the imaging capability of the lenses is very decisive for the homogenizing quality of a Köhler integrator. More lens channels will improve the light mixing; however, if the lenses are getting to small, diffraction effects will distort the flat-top uniformity.

2.2 The Fresnel Number

The diffraction effects at refractive lenses are described by the Fresnel number FN (Figure 4). The aperture of a lens with diameter Ø = 2a is broken into Fresnel zones, each indicating an optical path difference of one-half wavelength. The Fresnel number, FN, is the number of times the phase cycles through π as seen from an observation point at $z = f_E$.



$$FN = \frac{a^2}{\lambda f_E} \tag{1}$$

Figure 4. Fresnel Number as defined for a paraxial lens: Lens aperture Ø=2a, observation at the focal point $z = f_E$

When the Fresnel number is low, FN < 1, the observation point is in the "far field" (Fraunhofer Diffraction). When the Fresnel number is high, FN > 1, the observation point is in the "near field" (Fresnel Diffraction). The Fresnel number of a refractive lens corresponds to the number of Fresnel zones of diffractive lens with similar diameter and focal length.

Microlenses with small lens apertures and long focal lengths f_E have low Fresnel Numbers. A Fresnel number FN ≈ 1 will not provide good imaging. Such lenses behave more like pinholes and not like refractive lenses.

2.3 Non-imaging optical integrators

In literature, a Köhler integrator is also referred as facetted Köhler illumination, optical integrator, fly's eye condenser and imaging beam homogenizer. For an in-depth discussion we recommend Fred Dickey's book about laser beam shaping [6]. The terminus "imaging" makes much sense, because the basic mechanism is the imaging of the first array's sub-apertures to the object plane. As discussed, the imaging quality of the Köhler integrator matters. Another critical point is the precise alignment of the two lens arrays, the condenser lens and the optical axis of the incident beam. A less complicated version of an optical integrator is referred as non-imaging homogenizer [6]. A non-imaging homogenizer consists of one single lens array followed by a condenser lens. The lens array splits the incident beam into beamlets. These beamlets are then passed through the condenser lens and overlap at the object plane located in the back focal plane of the condenser lens. The condenser lens causes parallel bundles of rays to converge in the homogenization plane and is therefore also called a Fourier lens. It carries out a two-dimensional Fourier transformation. The intensity pattern in the homogenization plane is related to the spatial frequency spectrum generated by the lens array. To achieve a good flat-top uniformity using a non-imaging homogenizer, the lens array should distribute the light at equal intensities in the desired angular spectrum. Lens aberrations will lead to non-uniformities. As discussed by Masaki and Toyoda [7,8], a distortion aberration of X% might lead to an intensity variation of up to 4X%. The major problem of a non-imaging homogenizer is therefore the aberration correction. For plane wave incidence an aspherical lens profile, a parabolic lens profile will be the preferred solution. For non-collimated illumination, off-axis aberrations have to be considered. For a larger angular spectrum of the incident light, a spherical lens profile is usually the preferred solution.

2.4 Microlens Arrays for Köhler Integrators

Classical Köhler integrators were built by arranging individual lenses in a matrix. Beside the tight manufacturing tolerances for the individual microlenses and a possible misalignment in the array, the relatively high costs for mounting are the major drawbacks. Today, high-quality microlens arrays are manufactured by the use of wafer-based processes like photolithography and reactive-ion-etching or glass molding [9]. The challenge of these processes is the optimization of the lens profile, which is essential for the quality of the homogenization. For high power and applications in the DUV or UV wavelength range, the micro-optical components are manufactured in Fused Silica or CaF_2 [9]. Square-type lens apertures of the first microlens array LA_1 generate a square flat-top intensity distribution in the Fourier plane. Circular or hexagonal microlenses will generate a circular or hexagonal flat-top, respectively. Usually square-lens or crossed cylindrical-lens arrays are used to ensure a high filling factor. For monochromatic laser beams, a diffractive beam shaping solution is also very attractive. SUSS MicroOptics demonstrated recently 98% diffraction efficiency and less than 0.1% light remaining in the 0^{th} order for 193nm wavelength. In the following we will describe the basic properties of a Köhler integrator or imaging beam homogenizer using refractive microlens arrays.

2.5 Design rules for Köhler integrators

A microlens array is characterized by the pitch p_{LA}, i.e. the vertex clearance between two neighbouring lenses of the array. To show the correlation between the element-properties we used paraxial matrix method for a first approximation of the geometrical optic. For the description given here, we assume a point light source at an infinite distance in front of the first lens array. The size of the flat-top D_{FT} in the object plane FP depends on the focal lengths of the lenses within the array LA_1, LA_2 and the condenser lens and is given by

$$D_{FT} = p_{LA} \frac{f_{FL} \cdot (f_{LA1} + f_{LA2} - a_{12})}{f_{LA1} \cdot f_{LA2}}. \tag{2}$$

To fulfil the imaging conditions as mentioned above, the separation a_{12} between LA_1 and LA_2 has to be equal to the focal length of the second lenses f_{LA2}. Through this and together with the optical power of the condenser lens, the apertures are imaged to the object plane FP. With the determination that $a_{12} = f_{LA2}$, equation (2) is simplified to

$$D_{FT} = p_{LA} \frac{f_{FL}}{f_{LA2}}. \quad (3)$$

For imaging homogenizers the divergence θ (half angle) after the homogenized plane is given by

$$\tan\theta = \frac{1}{2} \cdot \left(\frac{d_{IN} - 2 \cdot p_{LA} + D_{FT}}{f_{FL}} + \frac{f_{LA2} \cdot p_{LA}}{f_{LA1} \cdot f_{FL}} \right), \text{ with } a_{12} = f_{LA2} \text{ and } s = 0, \quad (4)$$

where d_{IN} is the diameter of the incident beam and s the distance between the second lens array and the condenser lens. In this equation it is assumed that the separation s between the second lens array and the condenser lens is zero. Normally the divergence increases by increasing this separation.

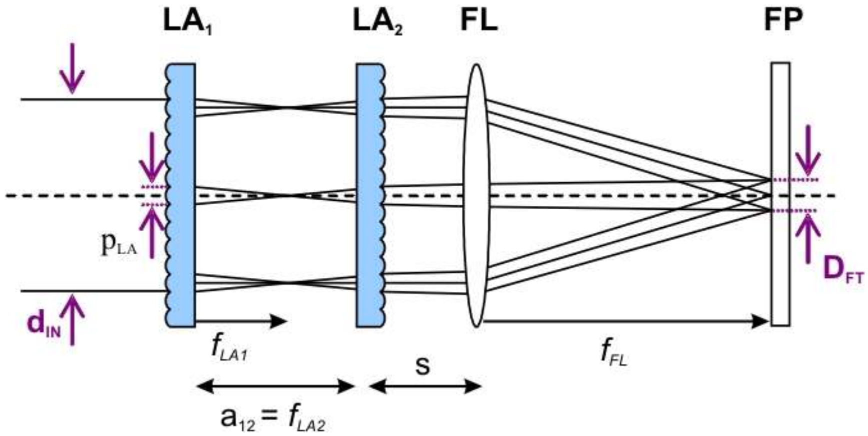


Figure 5. Köhler Integrator (imaging homogenizer): Two microlens arrays LA_1 and LA_2, one condenser lens FL.

Usually a Köhler integrator consists of two similar lens arrays with identical pitch p_{LA} and focal length ($f_{LA1} = f_{LA2} = f_{LA}$). For illumination with collimated beams, the light is focused into the plane of the second lens array. Care must be taken not to damage the second microlens array by focusing high-power laser beams into the lens material. For extended light sources, an image of the light source is found at the plane of the second microlens array. For Köhler integrators, the diameter of the individual beamlets at the second microlens array LA_2 must be smaller than the lens pitch to avoid overfilling of the lens aperture and the loss of light. This condition corresponds well with the design rules for Köhler illumination (Figure 1). An overfilling of the second lens array results in unwanted multiple-images in the plane FP. If an extended light source with diameter D_{source} is collimated with a positive spherical lens with a focal length $f_{CL,}$ the image size D_{image} at the second lens array is

$$D_{image} = D_{Source} \frac{f_{LA1}}{f_{CL}} \leq p_{LA}, \text{ if } a_{12} = f_{LA1} = f_{LA2}. \quad (5)$$

To avoid overfilling of lens apertures the pitch p_{LA} has to be larger than $D_{image.}$ For incident light with a significant beam divergence the diameter of the beamlets at the second microlens array scales with the beam divergence. The number of lenses N across the beam diameter d_{IN} is $N = d_{IN} / p_{LA}$.

3. KÖHLER INTEGRATORS FOR LASER BEAM SHAPING

Köhler illumination and Köhler integrators are widely used in many applications since more than a hundred years. These design concepts are now used for all kind of "modern" light sources, like lasers, VCSELs and LEDs. Especially for high-power lasers with poor beam quality like Excimer and YAG-lasers, a homogenizing solution is often mandatory to achieve the uniformity demanded by the different applications. We will now briefly summarize basic properties of laser beams and explain the limits and constrains in using Köhler integrators and homogenizers with laser beams.

3.1 Basic properties of laser beams

The modes of an optical resonator with the lowest order in the transverse direction (TEM00) are Gaussian modes, thus the Gaussian beam is the simplest case of laser beams. As the Fourier transformation of a Gaussian is also Gaussian, Gaussian beams have a Gaussian intensity profile at any location along the beam axis; only the beam radius varies. The deviation from a Gaussian beam shape can be quantified with the M^2 factor. A Gaussian beam has the highest possible beam quality, which is related to the lowest possible beam parameter product, and corresponds to $M^2 = 1$. However, a lot of laser sources produce laser beams with irradiance patterns much different from those of the Gaussian beam case. The simplest cases of these non-Gaussian beams are multimode laser beams [10]. More complex are Excimer lasers, the preferred laser source for DUV lithography and many applications in the fields of material processing and medical treatment. Excimer lasers provide an almost speckle-free illumination due to the poor spatial coherence.

3.2 Speckles

Speckles arise from the interference of light that has a random spatial phase modulation distributed over its wavefront. When traveling through a Köhler integrator, the different laser modes acquire different phase shifts and a speckle pattern is observed in the flat-top. The contrast of this speckle pattern depends on the coherence length of the transmitted beam. It will vanish if the optical path length difference between the fastest and slowest modes exceeds the longitudinal coherence length of the incoming laser beam [11].

3.3 Beam divergence

For a diffraction-limited Gaussian beam, the $1/e^2$ beam divergence half-angle is $\lambda / (\pi w_0)$, where λ is the wavelength (in the medium) and w_0 the beam radius at the beam waist. This equation is based on the paraxial approximation, and is thus valid only for beams with moderate divergence. A higher beam divergence for a given beam radius, i.e., a higher beam parameter product, is related to an inferior beam quality, which essentially means a lower potential for focusing the beam to a very small spot. If the beam quality is characterized with a certain M^2 factor, the divergence half-angle is

$$\Theta = \frac{M^2 \lambda}{\pi w_0} . \tag{6}$$

3.4 Array Generators

Köhler integrators or fly's eye condensers using two microlens arrays are widely used for laser beam homogenizing. However, using a Köhler integrator with a collimated coherent laser beam will have some significant drawbacks [12]. In the classical Köhler system the filament of a light bulb is an extended light source emitting incoherent light in a large angular range (Figure 1). As shown in Figure 2, one design rule for Köhler is that the images of the filament should almost fill the sub-apertures of the second microlens array LA_2. This ensures that the pupil plane of the imaging objective is filled with multiple images of the light source to allow optimum imaging of the object.

If a Köhler integrator is illuminated with a coherent and well collimated laser beam, the first microlens array LA_1 will form a sharp focal spot in each sub-aperture of the second microlens array LA_2. A matrix of coherent secondary point sources will be generated. The Köhler illumination will certainly work, i.e. each point source will generate a uniform "flat-top" illumination in the object plane. However, due to a limited number of point sources the flat-top will be illuminated by a discrete plane wave spectrum. For coherent illumination, the plane waves are coherent and will interfere in the object plane. A periodic fringe or spot pattern will be observed in the object plane of the Köhler integrator. These interference effects are demonstrated with for a Köhler integrator illuminated by a collimated laser beam of 670 nm wavelength. The results are shown in Figure 6. The pitch p_{LA} of the microlens arrays was 300 µm. The results show good agreement with theoretical calculations. The period of the spots is about 677 µm for a condenser lens of f_{FL} = 300 mm focal length.

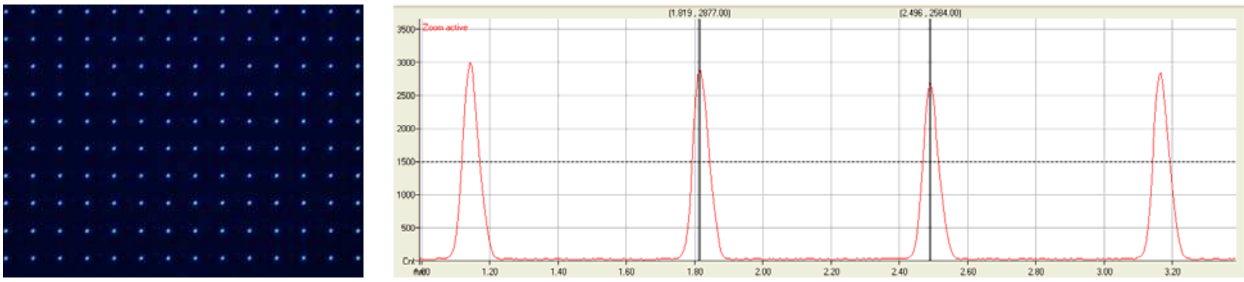


Figure 6. Measured intensity profile at object plane of Köhler integrator using microlens arrays with 300µm pitch and a condenser lens of 300mm focal length.

For illumination with a coherent and well collimated laser beam, the flat-top intensity profile in the object plane is subdivided into sharp peaks or lines. According to Streibl [13], each spot corresponds to the Fourier transformation of the light source, respectively to the angular divergence of the incident light before the integrator. The microlens pitch p_{LA} and the focal length of the condenser lens f_{FL} define the period Λ_{FP} in the Fourier plane. The period Λ_{FP} is given by:

$$\Lambda_{FP} = \frac{\lambda \cdot f_{FL}}{p_{LA}}. \tag{7}$$

The number of spots N is equivalent to the Fresnel number FN of the microlens array.

$$N = \frac{p_{LA}^2}{f_{LA}} = FN_{LA}. \tag{8}$$

This modulation of the flat-top by N x N sharp peaks is usually very surprising for an un-experienced engineer who simply wants to homogenize his collimated coherent laser beam.

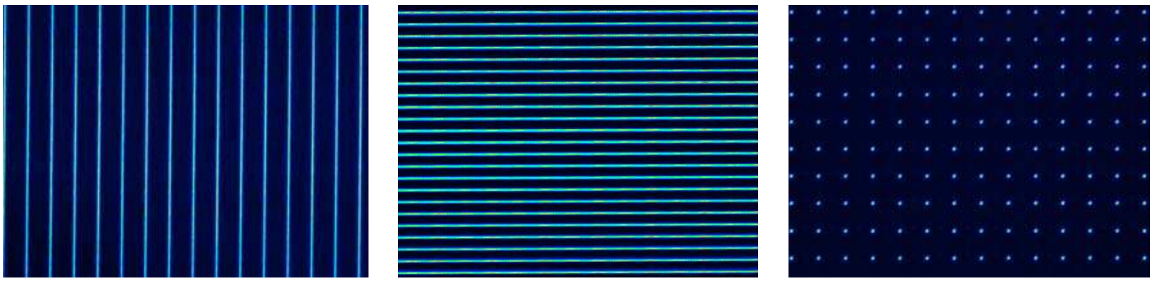


Figure 7. Line Generator (left) vertical, (mid) horizontal, (right) spot pattern of array generator.

As already suggested by Streibl [13], these well defined matrices of points or lines with equal intensity are well suited as array generators [Figure 7]. Typical applications for line and array generators are, e.g. hole drilling, skin treatment, fluorescence detection for bio-chips, or illumination of displays and MEMS mirror arrays. Array generators using Köhler integrators are quasi loss-less. No light appears outside the flat-top area and the spot pattern shows a very high contrast. Shaping the angular spectrum of the incident light allows generating patterns. Figure 8 shows the resulting spot array if a collimated laser beam is illuminating an axicon located prior to entering the Köhler integrator. The axicon generates a collimated annular beam. In the object plane an array of overlapping circles is observed. The size of the circles corresponds to the angular spectrum of the light after the axicon.

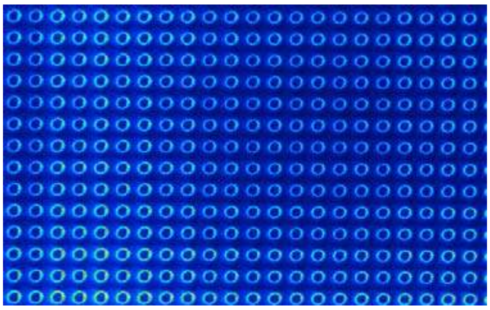


Figure 8. Array of overlapping circles generated by illuminating a microlens beam homogenizer with an annular beam generated by a plano-convex axicon.

For most other laser applications beside array generation, this strong modulation of the flat-top is un-acceptable and has to be avoided by any means. The simplest approach is to use a laser with low coherence, high beam divergence and high M^2. If this is not possible, the angular spectrum of the incident beam should be increased until the sub-apertures of the second lens array are slightly under-filled.

It is important to understand, that due to Talbot self-imaging [3, 14], all light interacting with periodic structures like the microlens arrays in the Köhler integrator, will always keep traces of the array's periodicity in its further propagation.

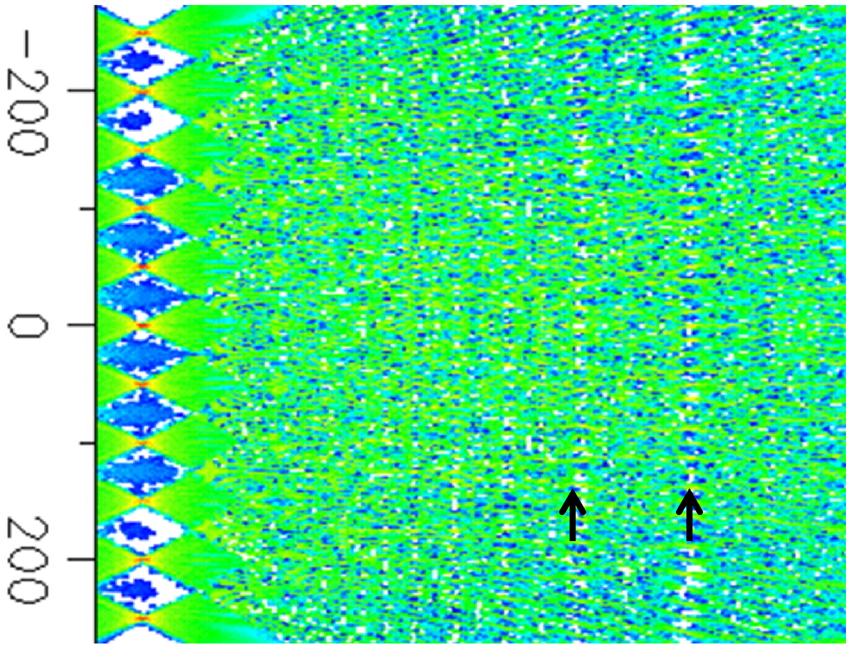


Figure 9. Diffraction simulation showing periodicity and Talbot planes behind a periodic microlens array. The arrows indicate the position of different fractional Talbot images.

This is a fundamental drawback if array optics is used with coherent and well collimated laser beams.

3.5 Köhler integrators using non-periodic microlens arrays

Wippermann et al. [15] recently proposed to use chirped microlens arrays in a wedge configuration as shown in Figure 10 (right). The variation of the lens array pitch breaks periodicity and generates a continuous spectrum in the object plane. The proposed wedge configuration avoids hole in the spectrum due to missing low frequencies in the array. This idea seems to be a promising approach; however, the required wedge does not allow standard wafer-level manufacturing of the microlens arrays. In addition, the laser beam diameter must match well with the size of the microlens array. A different approach is a dynamic change of the periodic pattern by using a rotating diffuser.

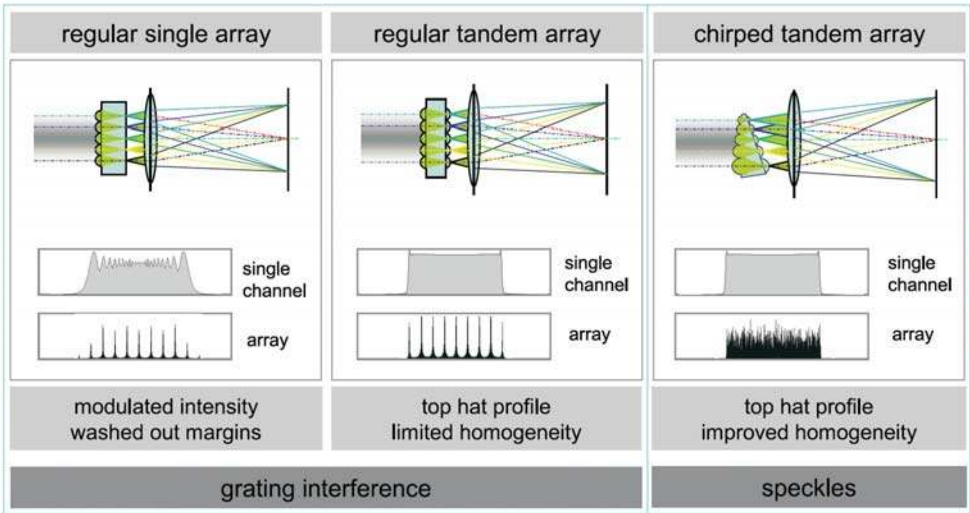


Figure 10. Comparison of Köhler integrators with different microlens arrays according to Wippermann[1]

3.6 Speckles

Speckles arise from the interference of light that has a random spatial phase modulation distributed over its wavefront. When traveling through Köhler integrator, the different laser modes acquire different phase shifts and a speckle pattern is observed in the flat-top. The contrast of this speckle pattern depends on the coherence length of the transmitted beam. It will vanish if the optical path length difference between the fastest and slowest modes exceeds the longitudinal coherence length of the incoming laser beam [11]. A dynamic change in the speckle pattern, e.g. by using a rotating diffuser, will allow reducing speckle effects in the object plane. The residual granularity contrast scales with $1/\sqrt{m}$, whereas m is the number of different speckle pattern during integration time.

3.7 Rotating Diffusers

Rotating ground glass diffusers are well known from microscopy and laser interferometers. A rotating diffuser plate is usually placed in a separate telescope as shown in Figure 11. The diffuser is rotating, resulting in a temporal variation of the pattern observed in the object plane. Shifting the diffuser position in the telescope allows changing the size and angular spectrum of the secondary light source generated by the rotating diffuser.

[1] Image: Courtesy of Frank Wippermann, IOF Jena, published in [15]

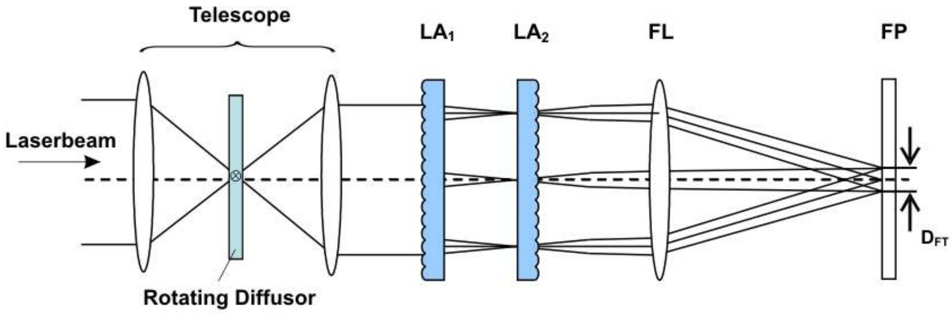


Figure 11. Schematic setup of a rotating diffuser used with a microlens homogenizer.

Experimental results of combining a rotating diffuser and a Köhler integrator are shown in Figure 12. A diode laser of 670 nm wavelength of was used. A microlens array of 250 µm pitch, Fresnel number FN ≈ 15, was used.

For a condenser lens of 40 mm focal length a flat-top 6.4 x 6.4 mm^2 is obtained. As shown in Figure 12 (right), the interference effects are well smoothed out for temporary integration in the object plane.

Figure 12. Intensity distribution distributions in the object plane of Köhler integrator demonstrating the application of a rotating diffuser: (left) no diffuser, (right) rotating diffuser similar to Figure 11.

For pulsed lasers like Excimer and Nd:YAG, the pulse length of typically some nanoseconds is usually too short to use rotating diffusers. Two rotating diffusers (at inverse rotation) [16], stair case beam splitters and pulse stretchers are used to reduce interference and speckle contrast for these lasers.

3.8 Design and manufacturing of random diffusers

Ground glass diffusers (Figure 13, left) are manufactured by grinding and lapping. Due to their rough surface structure a significant amount of the incident light is diffracted to very large angles and lost in the optical system. Wafer-based microfabrication techniques, using photolithography and isotropic wet etching allow the manufacturing of precisely shaped high-efficient random diffusers (Figure 13, center) providing a desired far-field intensity distribution, like e.g. a Gaussian, Super-Gaussian or flat-top. This technology also allows the manufacturing of 1-dimensional random diffusers.

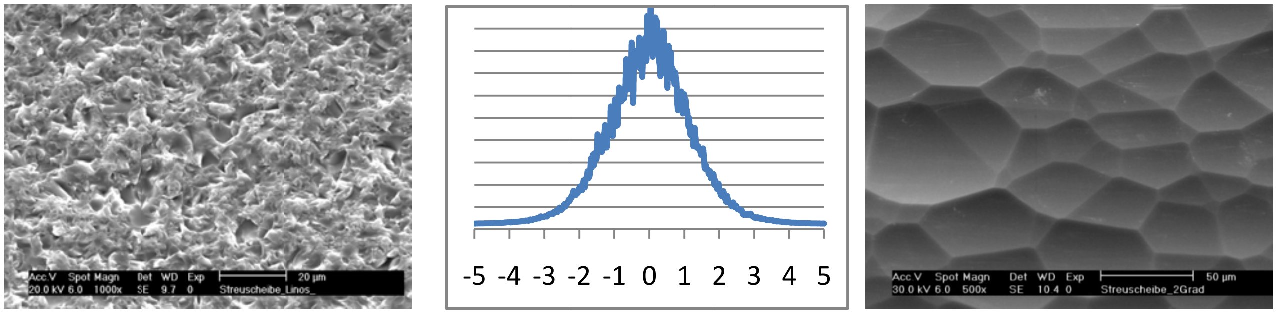


Figure 13. SEM pictures of (left) ground glass diffuser (FWHM ≈ ±10°) and (middle) high-efficiency random diffuser in Fused Silica. Microfabrication techniques, using photolithography and wet etching allow precise shaping of the far-field intensity distribution. Angular distribution (right) of a SUSS high-efficiency diffuser measured in goniometer.

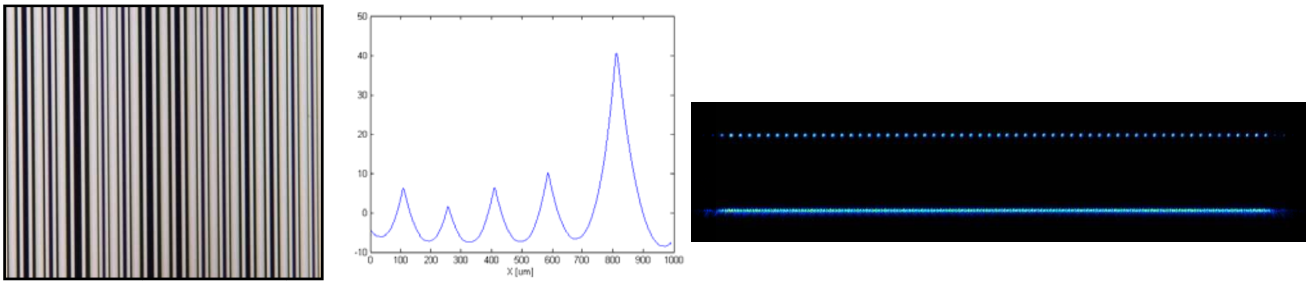


Figure 14. (Left) image of a mask for a statistical linear diffuser, (center) stylus measurement of the profile and (right) spot pattern (right, top) from 1D Köhler integrator and (right, bottom) using additional linear random diffuser for smoothing.

1-dimensional random diffusers consist of a pattern of arbitrary and statistically placed diffusing elements as shown in Figure 14. These diffusers are generated by isotropic etching of a mask of slits of fixed width that are statistically positioned across a fused silica substrate [17]. Long etch times generate diffusers with large radius of curvature and consequently small angular diffusion. By changing the radius of curvature it is possible to adjust the angular distribution of the linear diffuser, wide angles such as 20° to 60° are possible as well as diffusers with less than 1°. Linear diffusers are ideal for 1D line applications or for asymmetric laser beams where anisotropic diffusion properties are required. Such diffusers are useful in improving the uniformity of line homogenizers and laser light sheets as shown in Figure 14.

4. CONCLUSION

Köhler integrators, also known as fly's eye condensers, optical integrators or beam homogenizers, are well established for illumination systems since more than 100 years. Today, wafer-based manufacturing techniques for high-quality microlens arrays provide cost-efficient Köhler integrators for many laser applications from DUV to Infrared. However, interference and speckle effects significantly influence the flat-top uniformity for well collimated and coherent lasers. Usually best results are achieved by using a combination of a Köhler integrator and random diffusers.

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