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Beam shaping optics to enhance performance of interferometry techniques in grating manufacture

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ABSTRACT

Improving of industrial holographic and interferometry techniques is of great importance in interference lithography, computer-generated holography, holographic data storage, interferometry recording of Bragg gratings as well as gratings of various types in semiconductor industry. Performance of mentioned techniques is essentially enhanced by providing a light beam with flat phase front and flat-top irradiance distribution. Therefore, transformation of Gaussian distribution of a TEM_{00} laser to flat-top (top hat, uniform) distribution is an important optical task. There are different refractive and diffractive beam shaping approaches used in laser industrial and scientific applications, but only few of them are capable to fulfil the optimum conditions for beam quality demanding holography and interferometry. As a solution it is suggested to apply refractive field mapping beam shaping optics πShaper, which operational principle presumes almost lossless transformation of Gaussian to flat-top beam with flatness of output wavefront, conserving of beam consistency, providing collimated low divergent output beam, high transmittance, extended depth of field, negligible wave aberration, and achromatic design provides capability to work with several lasers with different wavelengths simultaneously. High optical quality of resulting flat-top beam allows applying additional optical components to build various imaging optical systems for variation of beam size and shape to fulfil requirements of a particular application. This paper will describe design basics of refractive beam shapers and optical layouts of their applying in holography and laser interference lithography. Examples of real implementations and experimental results will be presented as well.

Keywords: beam shaping, flat-top, holography, interferometry, interference lithography, Bragg gratings, Holographic Data Storage, homogenizing.

1. INTRODUCTION

Various implementations of interferometric techniques are used in industrial applications, for example formation of various periodic nanostructures by lithography in semiconductor industry, recording Bragg gratings, as well as in various holography applications: Computer Generated Holography (CGH), Holographic Data Storage (HDS), hologram mastering using Spatial Light Modulators (SLM) like Liquid Crystal on Silicon (LCoS) or Digital Mirror Devices (DMD).

Typically, the intensity distribution of laser sources is described by Gaussian function provided by physics of creating the laser radiation. This Gaussian profile is naturally inhomogeneous, which is rather a source of problems in interference techniques: variation of brightness of reproduced images, instability of recording processes, reduced image contrast, variation of size and shape of recorded periodic objects, inconvenience in realization of optical setups. Therefore, transformation of laser beam intensity profile from Gaussian to uniform one (flat-top, tophat) is an important optical task. A specific demand of interference techniques is in strict requirements to flatness of phase front of a laser beam that should be conserved while any irradiance profile transformations, i.e. *flatness of both phase front and irradiance distribution should be realized simultaneously*. There are several beam shaping techniques applied in modern

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laser technologies, some of them, like integration systems based on arrays of microlenses, micromirrors, prisms, cannot be applied since their physical principle implies destroying the beam structure and, hence, leads to loss of spatial coherence. Other techniques: truncation of a beam by an aperture, attenuation by apodizing filters allow obtaining acceptable in many cases homogeneity of irradiance profile, but evident disadvantage of these techniques is essential loss of costly laser energy. To meet the demands of modern interferometry techniques it is suggested to apply beam shaping systems built on the base of field mapping refractive beam shapers like π*Shaper*, which operational principle implies almost lossless transformation of laser irradiance distribution from Gaussian to flat-top, conserving of beam consistency, flatness of output phase front, low divergence of collimated output beam, high transmittance, extended depth of field, capability to operate with TEM_{00} or multimode lasers, implementations as telescopes or collimators.

2. FIELD MAPPING REFRACTIVE BEAM SHAPERS

2.1 Basics of optical design

The design principles of refractive beam shapers of field mapping type, like π*Shaper*, are well-known and described in literature[1-6].

Most often these devices are implemented as telescopic systems with two optical components, it is implied that wave fronts at input and output are flat, the transformation of irradiance profile from Gaussian to uniform is realized in a controlled manner, by accurate introducing of wave aberration by the first component and further its compensation by the second one, Fig.1, top.

Thus, the resulting collimated output beam has uniform irradiance and flat wave front; it is characterized by low divergence – almost the same like one of the input beam. In other words, the field mappers transform the irradiance distribution *without deterioration of the beam consistency and without increasing of beam divergence*.

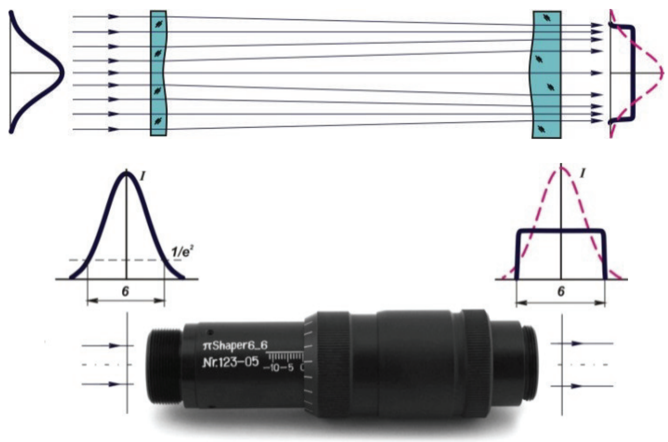

Figure 1. Refractive field mapping beam shaper π*Shaper*.

Shortly the main features of refractive field mappers are:

- refractive optical systems transforming Gaussian to flat-top (uniform) irradiance distribution;
- transformation through controlled phase front manipulation – 1st component introduces spherical aberration required to re-distribute the energy, then 2nd component compensates the aberration;
- output beam is free of aberrations, phase profile is maintained flat, hence, low output divergence;
- TEM_{00} and multimode beams applied;
- collimated output beam;
- beam profile is stable over large distance;
- implementations as telescopic or collimating optical systems; achromatic optical design - beam shaping for several lasers simultaneously;
- Galilean design, no internal focusing.

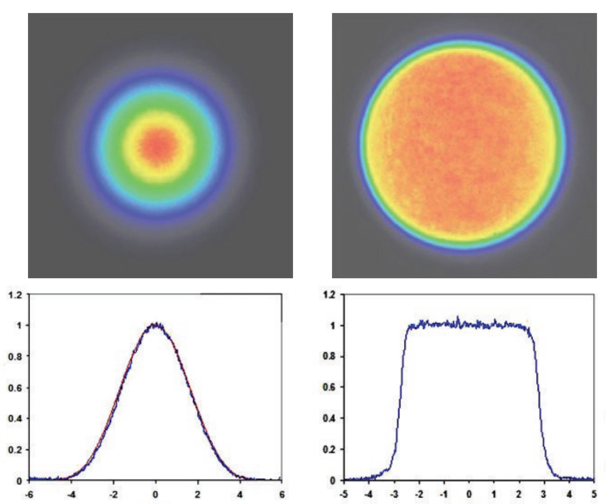

Figure 2. Experimental intensity profiles:
left – Input TEM_{00} beam, right - after the π*Shaper*.

Example of beam shaping for Nd:YAG laser is presented in Fig.2.

2.2 Propagation of flat-top beams in space

It is usual to characterize beam shaping optics by the working distance – the distance from last optical component to a plane where a target irradiance profile, flat-top or another one, is created. The working distance is an important specification for diffractive beam shapers and refractive homogenizers (or integrators) based on multi lens arrays. But in case of the field mapping beam shapers the output beam is *collimated* and, hence, instead of a definite plane where a resulting irradiance profile is created, there exists certain space after a beam shaper where the profile is kept stable. In other words, the working distance isn't a specification for the field mapping beam shapers, it is better specify the depth of field (DOF) after a beam shaper where resulting irradiance profile is stable. This DOF is defined by diffraction effects happening while a beam propagating and depends on wavelength and beam size.

When a TEM_{00} laser beam with Gaussian irradiance distribution propagates in space its size varies due to inherent beam divergence but the irradiance distribution stays stable, this is a famous feature of TEM_{00} beams that is widely used in practice. But this brilliant feature is valid for Gaussian beams only! When light beams with non-Gaussian irradiance distributions, for example flat-top beams, propagate in space, they get simultaneously variation of both size and irradiance profile. Suppose a coherent light beam has uniform irradiance profile and flat wave front, Fig. 3, this is a popular example considered in diffraction theory[7,8,9], and is also a typical beam created by field mapping refractive beam shapers converting Gaussian to flat-top laser beam.

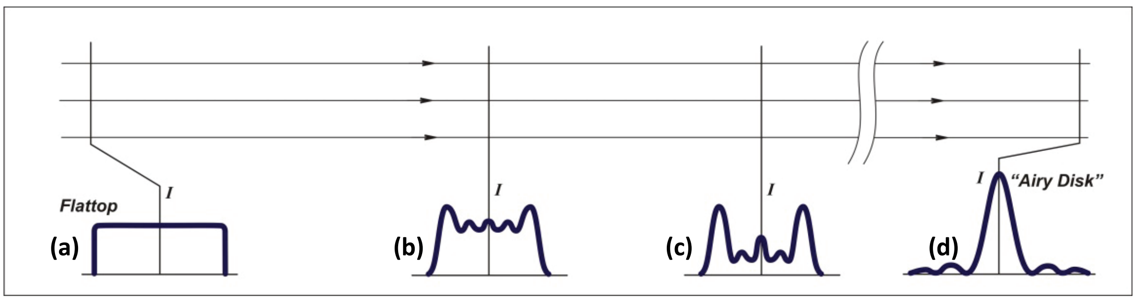

Figure 3. Irradiance profile variation by a flat-top beam propagation.

Due to diffraction the beam propagating in space gets variation of irradiance distribution, some typical profiles are shown in Fig. 3: at certain distance from initial plane with uniform irradiance distribution *(a)* there appears a bright rim *(b)* that is then transformed to more complicated circular fringe pattern *(c)*, finally in infinity (so called far field) the profile is featured with relatively bright central spot and weak diffraction rings *(d)* – this is the well-known distribution described by "Airy disk" function which is result of Fourier-Bessel or Hankel transform for a circular beam of uniform initial irradiance[7,8]. Mathematically the "Airy disk" is described by

$$I(\rho) = I_0 \left[\frac{J_1(2\pi\rho)}{2\pi\rho} \right]^2 \tag{1}$$

where $I(\rho)$ is irradiance, J_1 is the Bessel function of 1st kind, 1st order, ρ is polar radius, I_0 is a constant.

Evidently, even a "pure" theoretical flat-top beam is transformed to a beam with essentially non-uniform irradiance profile. There exists, however, certain propagation length where the profile is relatively stable, this length is in reverse proportion to wavelength and in square proportion to beam size. For example, for visible light, single mode initial beam and flat-top beam diameter 6 mm after a π*Shaper 6_6* the length where deviation from uniformity doesn't exceed $\pm$10% is about 200-300 mm, for the 12 mm beam it is about 1 meter.

There are many laser applications where conserving a uniform irradiance profile over certain distance is required, for example holography, interferometry; the extended DOF is also very important in industrial techniques to provide less tough tolerances on positioning of a workpiece. As a solution to the task of providing a necessary resulting spot size with conserving the flat-top profile over extended DOF it is fruitful to apply imaging techniques.

3. IMAGING OF FLAT-TOP BEAMS

3.1 Telecentric imaging of *πShaper* output

Imaging technique is a powerful tool to building complex beam shaping systems on the base of refractive beam shapers like π*Shaper*, essential features of this approach are considered in paper[10]. Here we emphasize on most important for practice aspects and consider in details the telecentric imaging system, Fig. 4, that is practically a perfect tool to magnify or de-magnify the laser beams in interference techniques, holography with conserving the flatness of phase front and irradiance profile.

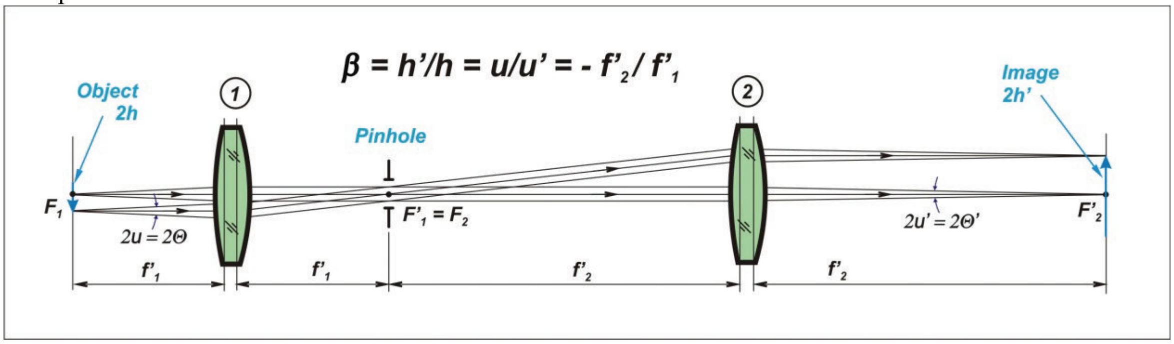

Figure 4. Telecentric imaging.

The optical system providing telecentricity in both spaces of the *Object* and the *Image* is composed from two positive optical components in such a way the back focus of the 1st component coincides with the front focus of the 2nd component, i.e. the optical system presents the Keplerian telescope, which famous feature is capability to create real image. Since the optical power of this telecentric system is the flat phase front in the *Object* space is mapped to the flat phase front in the *Image* space,

- the transverse magnification of the optical system is constant and doesn't depend on position of the *Object*,
- if the Object is located in front focal plane of 1st component its *Image* is in back focal plane of 2nd component.

From the point of view of geometrical optics an *Image* is always created by a beamlet of rays emerging from a particular point of an *Object*, therefore in Fig. 4 there are shown beamlets of divergence *2u* from couple of *Object* points. In case of laser beams the divergence of beamlets corresponds approximately to divergence of a laser beam *2Θ*, i.e. is very small for TEM_{00} beams, and the irradiance profile behaviour in a telecentric system should be carefully analysed using diffraction theory.

3.2 Extended depth of field (DOF)

Another important feature of imaging of low divergent laser beams is extended DOF; this effect is illustrated in Fig. 5.

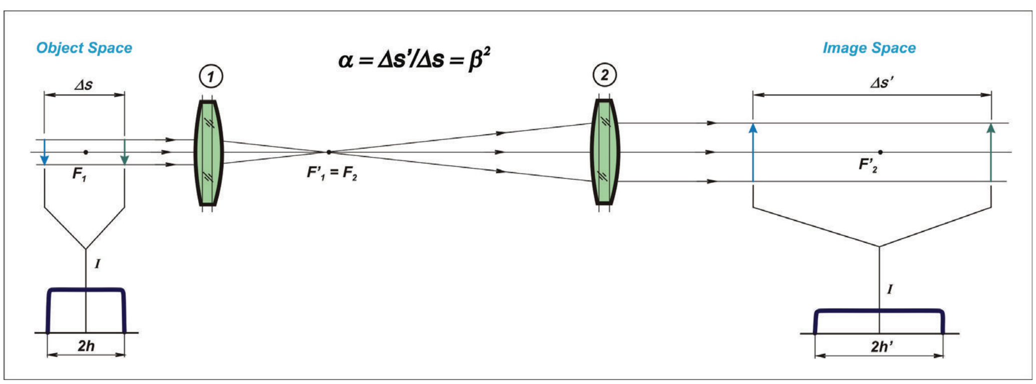

Figure 5. To evaluation of depth of field in imaging layout.

The *Object* at the exit of the *πShaper* can be implemented as a physical aperture or iris diaphragm, and then the *Image* will have very sharp edges and repeat the shape of that aperture. If no apertures applied and output collimated beam simply propagates towards the imaging lens the *Object* has no a definite plane and whole space after the *πShaper*, where the irradiance profile is flattop, will be mapped to a corresponding space in the *Image* side. As discussed in paragraph 2.2 that length Δs of stable profile in the *Object* space depends on wavelength and beam size, it can achieve values of several hundreds of mm or several meters depending on applied laser and *πShaper*. Hence, the beam profile is stable over relatively long length $\Delta s'$ in the *Image* space as well, in other words the extended DOF is provided. From the laws of geometrical optics[9] the DOF length $\Delta s'$ in *Image* space is proportional to longitudinal magnification α of an imaging system that is equal to square of the transverse magnification β^2.

3.3 Spatial Filtering

The spatial filtering[7] is very important in holography; this technique is used to "clean" the image by removing parasitic interference patterns originated by dust on optics or imperfections of a laser source. A general approach is to apply a pinhole locating in a certain plane of optical system where a laser beam is focused; the pinhole diameter has to be chosen in such a way that central "0" order lobe of diffraction pattern in focal plane passes through the pinhole, while the rest part corresponding to 1st and higher diffraction orders is clipped – evidently, that diameter has to be equal to diameter of first dark ring of diffraction point spread function (PSF), corresponding formulas are in details described in literature[7,8]. This approach works perfect when TEM_{00} laser beams with Gaussian or close to Gaussian irradiance profiles are applied and final holographic image can have Gaussian-like intensity. However in case of flat-top beams the spatial filtering technique should be modified by enlarging of the pinhole diameter. Let's consider the layout in Fig. 4 where *πShaper* output (the *Object*) is imaged in working space using the Keplerian telescope realizing telecentric projection. As we discussed earlier the *Object* beam with uniform irradiance is focused between the telescope optical components, and the irradiance distribution in common focal plane marked as "$F'_1=F_2$" is just *"Airy disk"* described by the Eq.(1), then the uniform irradiance distribution is restored in the *Image* plane. Evidently, for the spatial filtering it is logic to locate a pinhole just in plane "$F'_1=F_2$". However if its diameter is equal to diameter of first dark ring of the *"Airy disk"* the restored in the *Image* plane irradiance distribution will be practically Gaussian but not uniform (flat-top), since the 1st and higher order diffraction rings would be clipped and wouldn't take part in interference in the *Image* plane. To restore the uniform irradiance profile in the *Image* plane it is necessary to provide the majority of the beam energy transmitting through the pinhole, and not only the central lobe but also several non-zero diffraction orders to interfere in the *Image* plane. Analysis of the beam energy within a circle containing several diffraction orders can be performed using the Eq.(1) for conditions of a particular optical system. The Table 1 contains results of PSF calculations by focusing a beam of λ = 442 nm, uniform irradiance and 6 mm diameter by a perfect objective of focal length 50 mm, here diffraction order is equal to a number of a dark ring.

Table 1. Calculations for the *"Airy disk"* PSF.

Diffraction order	Radius of dark ring, μm	Energy within dark ring, %	Energy of hell ring, %
0	0		83,77
1	4,4	83,77	7,22
2	8,1	90,99	2,77
3	11,8	93,76	1,47
4	15,6	95,23	0,91
5	19,1	96,14	0,62
6	22,8	96,76	0,45
7	26,6	97,21	0,34
8	30,4	97,55	0,27
9	34,2	97,82	0,21
10	37,6	98,03	0,18
11	41,3	98,21	0,15
12	45,3	98,36	0,13
13	48,8	98,49	0,11
14	52,3	98,60	0,10
15	56,0	98,70	0,09
16	59,5	98,79	0,07
17	63,3	98,86	

In this system, the 9 μm diameter pinhole would provide "usual" spatial filtering when only central lobe ("0" order) is

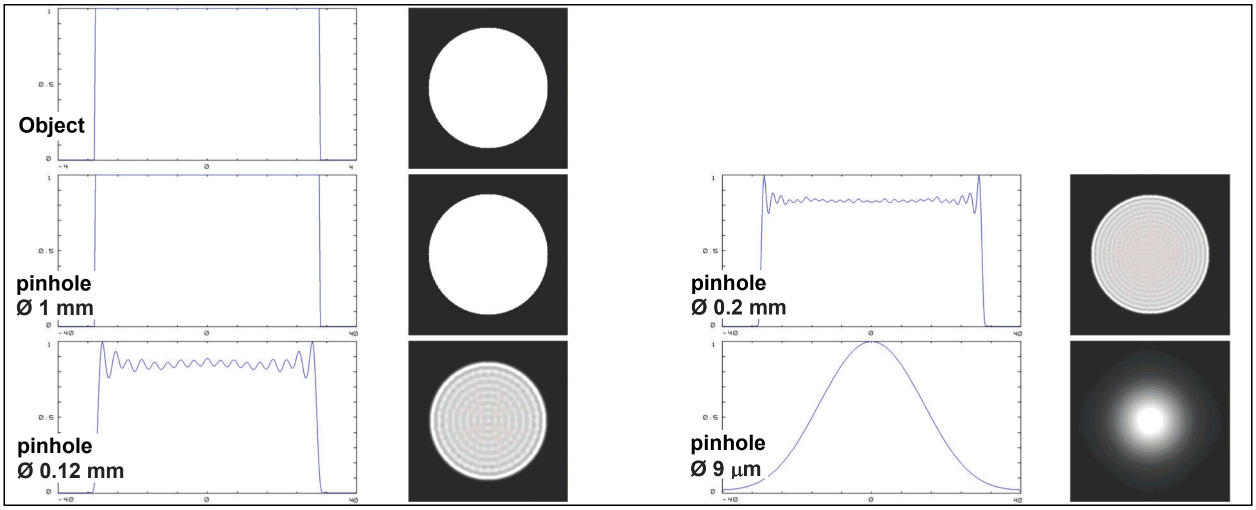

Figure 6. Irradiance distributions in Image plane (layout of Fig. 4) by spatial filtering with various pinholes.

passed, while 120 μm diameter pinhole transmits almost 99% of energy, hence one can expect acceptable restoring of uniform irradiance distribution in *Image* plane of the system in Fig. 4.

Analysis of the irradiance distribution can be done by calculations on the base of the well-known Fresnel-Kirchhoff diffraction integral[7,8], in practice for this purpose numerical methods are used, in this research there was used optical design software Zemax, particularly the module of physical optics propagation. Results of calculations for optical system in Fig. 4 with pinholes of various diameters are presented in Fig. 6. There is good correspondence between the earlier considered basic ideas of spatial filtering with using enlarged pinhole and results of numerical simulation for the *Image* irradiance: 1) practically Gaussian profile with 9 μm pinhole (central lobe), 2) profile with deviation from uniformity approx. ±5% in case of pinhole diameter 0.12 mm (almost 99% of energy), that is acceptable in many applications, 3) smoother profile with deviation from uniformity approx. ±2% is achieved when pinhole diameter 0.2 mm.

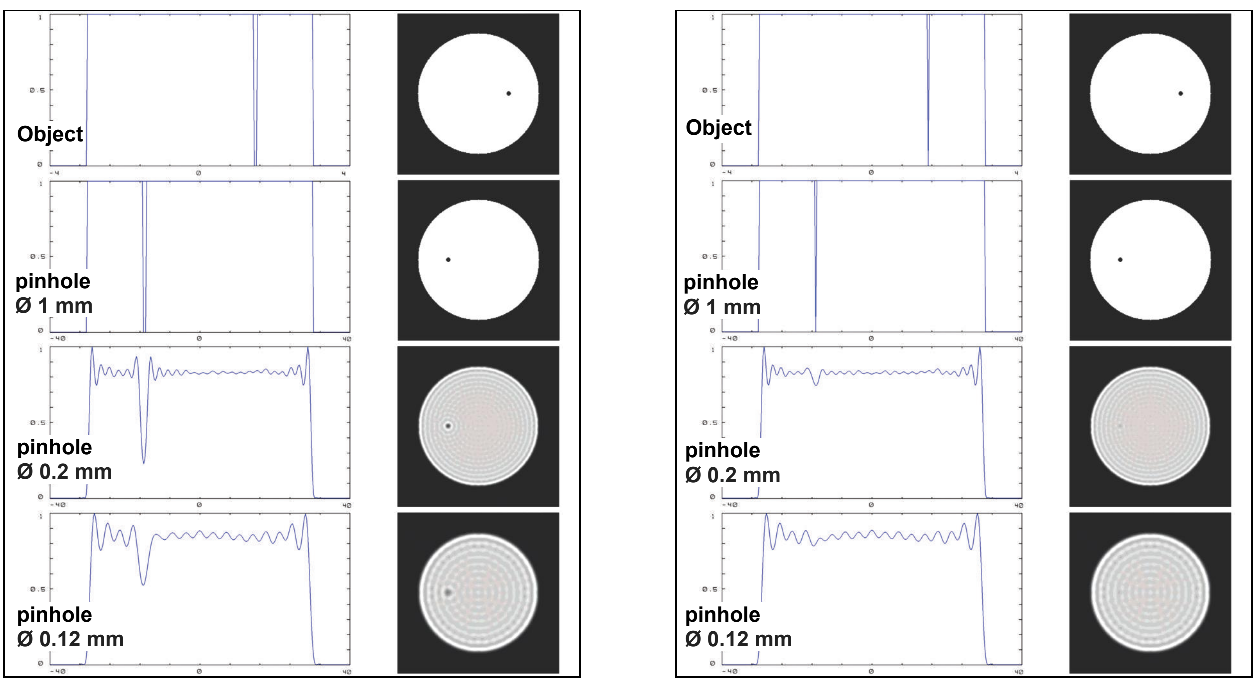

Figure 7. Simulation of spatial filtering of dust on the *Object* (Fig. 4):
on left - particle of Ø 0.1 mm, on right - particle of Ø 0.05 mm.

The software used for calculations allows also simulating spatial filtering of some defects of optical system like dust on the *Object* or lenses, some results of these simulations are shown in Fig. 7. There are considered defects in form of black opaque particles Ø0.1 mm and Ø0.05 mm, Fig. 7 top, and presented their images in the *Image* plane (layout of Fig. 4) under condition of spatial filtering with using pinholes of various diameters. Evidently, the image contrast of Ø0.1 mm particle is strongly reduced with Ø0.12 mm pinhole, while the image of Ø0.05 mm particle is practically negligible even with Ø0.2 mm pinhole.

Similar analysis is carried out for the case of a particle on 1st lens of optical component (1) (Fig. 4). Results are presented in Fig. 8 and 9, they are, basically, similar to ones in Fig. 7, that demonstrates importance of providing the same level of cleanness for all optical surfaces of an optical system.

The results of mathematical simulation confirm the principle capability of the enlarged pinhole to provide simultaneously irradiance uniformity of the *Image* field and suppress contrast of parasitic patterns from small particles or dust by means of spatial filtering of high frequency signal components. In practice the particles are typically of smaller than 0.05 mm size and aren't fully opaque, therefore contrast of parasitic images would be more suppressed is real applications.

An optimum pinhole diameter depends on features of a particular optical layout, therefore it is recommended to apply in real holography applications an iris diaphragm and choose its optimum diameter by analyzing the quality of resulting pattern from the point of view of intensity homogeneity and contrast of parasitic pattern from dust and other imperfections.

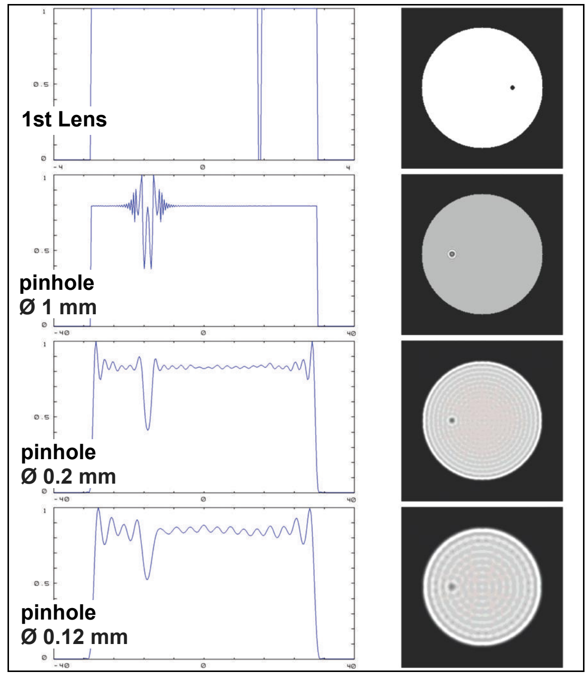

Figure 8. Simulation of dust on 1st Lens, particle of Ø0.1 mm.

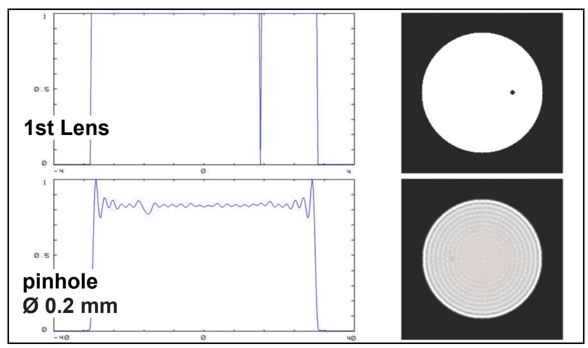

Figure 9. Simulation of dust on 1st Lens, particle of Ø0.05 mm.

3.4 Beam shaping layout in holography

Example of one of implementations of the optical system in Fig. 4 is presented in Fig. 10. This is the optical layout of the experimental system applied at the University of Sheffield[11] for CGH, where the laser irradiance profile is transformed in order to uniformly illuminate an SLM. Divergent Gaussian laser beam from TEM_{00} fiber coupled laser is transformed by the π*Shaper* to collimated flat-top beam, the output of the π*Shaper* is considered as an *Object* plane for the telecentric imaging system. Since the π*Shaper* conserves low divergence of laser beam, the irradiance profile after it gets transformation due to diffraction that is similar to one shown in Fig. 3. Therefore, near the lenses, Fig. 10, the irradiance distribution isn't uniform; it is typically characterized by appearing some diffraction rings, a particular profile depends on wavelength, beam size and distance from the *Object* to lenses. According to the diffraction theory the irradiance distribution in a certain plane is result of interference of light diffracted from previous plane of observation.

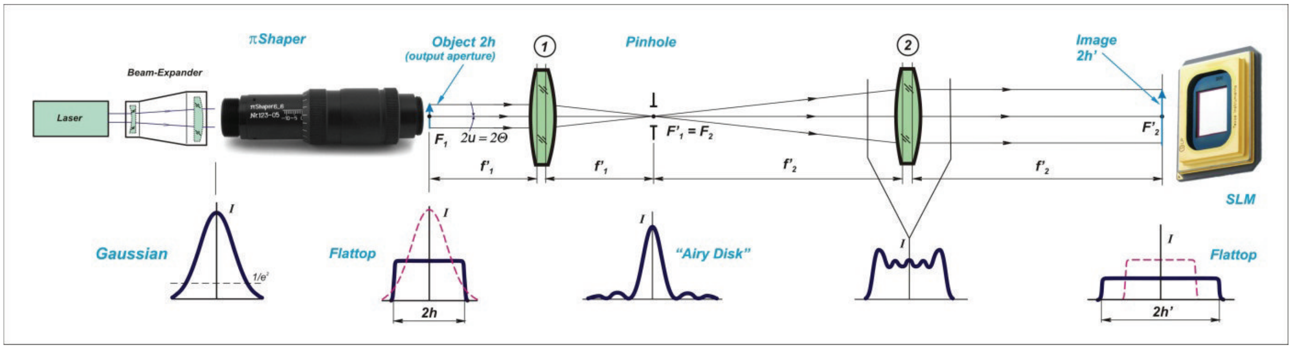

Figure 10. Example of beam shaping system in holography.

One of well-known conclusions of that theory is similarity of irradiance distribution in optically conjugated *Object* and *Image* planes[7,8]: *if the irradiance distribution is uniform in the Object plane, it is uniform in the Image plane as well*; and the profile at the π*Shaper* output aperture will be repeated in the *Image* plane of that aperture, herewith the resulting spot size is defined by transverse magnification β. Hence, if an SLM is located in the *Image* plane the incident radiation will be characterized by flat phase front and flat-top intensity profile.

The lenses shown in the example in Fig. 10 are just singlets, but for high quality imaging more sophisticated optical systems should be applied, for example aplanats or microscope objectives. Calculation of parameters of a particular imaging setup can be done using well-known formulas of geometrical optics[9].

The irradiance distribution in back focal plane of 1st lens, marked in Fig. 10 as "$F'_1=F_2$", is just "Airy disk", i.e. essentially non-uniform one. Summarizing results of this example one can see that uniform irradiance after π*Shaper*, the Object plane, is transformed to non-uniform irradiance in area around the lenses, to essentially non-uniform "Airy disk" distribution in back focal plane of 1st lens, and finally is restored to uniform irradiance profile in the Image plane as result of interference of diffracted beam.

An important conclusion for practice is that *it doesn't matter how the irradiance profile is transformed along the beam path, since the irradiance distribution in the Image plane repeats the Object plane distribution with taking into account transverse magnification*. Since the *Image* is a result of interference of light beams being emitted by the *Object* and diffracted according to physics of light propagation, it is necessary to take care for transmitting of full light energy through a system and *avoid any beam clipping*.

The described optical system is used at the University of Sheffield in holography installation with SLM in the form of a Texas Instruments DMD to project CGH images onto non-planar surfaces. Experimental results[12] demonstrated essential improvement of this technique by homogenizing of illumination of SLM, for example it has become possible to reproduce arbitrary locating in space light objects of arbitrary shape and to realize the 3D-lithography.

The considered approach of building beam shaping optical systems is also suggested in other holography applications like HDS[13]. It is also successfully applied in in interference-based techniques for creating periodic structures in various industrial technologies, one of them is considered in next paragraph.

3.5 Beam shaping in interference lithography

Laser interference lithography (LIL) is a technique to create micro- and nanoscale periodic structures over a large area without the use of complex optical systems or photomasks. One of LIL implementations is based on using Lloyd's mirror[14] providing interference of collimated beams under big angle to create gratings on a wafer with period of several hundred nanometres; this optical approach is illustrated in Fig. 11: the sample is illuminated by direct beam and reflected beam interfering at 90° angle.

Characteristic intensity distributions and resulting theoretical interference patterns are presented in Fig. 12 for (a) Gaussian and (b) flat-top laser beams; images from left to right:

- interferometry layout,
- intensity distribution of incident beam,
- 1D grating,
- 2D grating recorded by 2-step exposure with rotating the sample at 90°after the first exposure.

The presented results of theoretical simulation of periodic patterns demonstrate explicitly advisability of using uniform intensity of collimated incident light to provide periodic structures of regular line or dot size and shape over whole recording field, which is not realizable when the Gaussian laser beam applied.

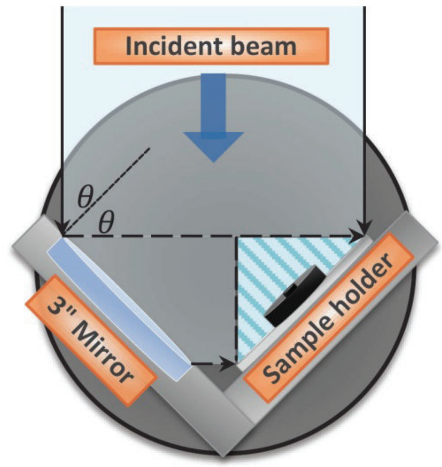

Figure 11. Optical layout of Lloyd's mirror interferometry.
(*Courtesy of NSYU, Taiwan*)

To provide illumination of the Lloyd's mirror interferometry setup by a beam of flat phase front and flat-top intensity profile one can apply the optical layout described in previous paragraph and presented in Fig. 10, where the SLM has to be replaced by the Lloyd's mirror. This approach of building the optical system is applied in experimental and industrial LIL installations described in article[14].

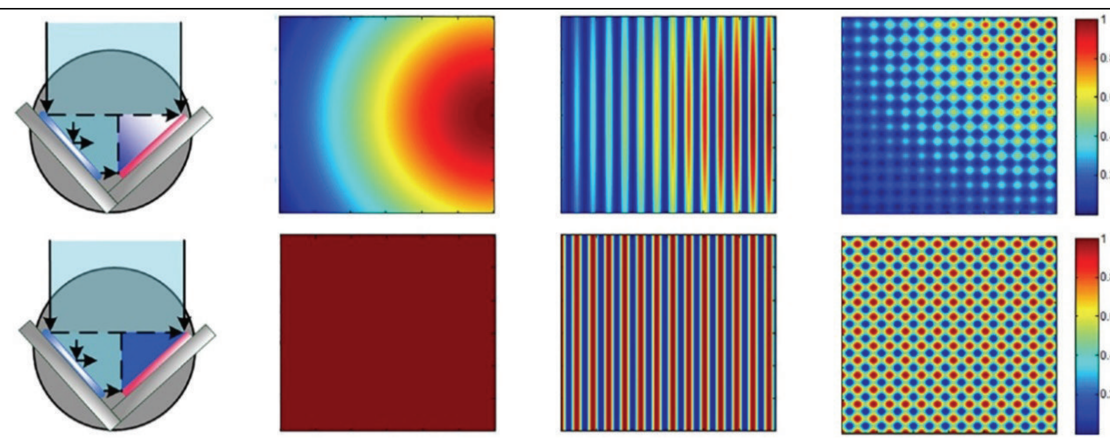

Figure 12. Calculated energy distributions of the laser beam on the sample and the corresponding dose modulation profiles in the formation of 1D and 2D gratings, respectively: (a) Lloyd's mirror interferometry with a Gaussian laser intensity distribution and (b) Lloyd's mirror interferometry with a flat-top laser intensity distribution.
(*Courtesy of NSYU, Taiwan*)

4. EXPERIMENTAL RESULTS

The optical system described in previous paragraph is realized in National Sun Yat-sen University, Taiwan in frame of a project to enhance performance of the *Laser Interference Lithography* applied to form periodic nano structures.

It was applied the TEM_{00} UV laser, which intensity distribution was transformed to uniform one using beam shaping optics on the base of π*Shaper 6_6_NUV*. Measured input and output intensity profiles are presented in Fig. 13; radiation of the laser has quite symmetric Gaussian distribution, therefore intensity profile of the transformed beam is characterized by high uniformity which together with flat phase front are optimum for the LIL technology.

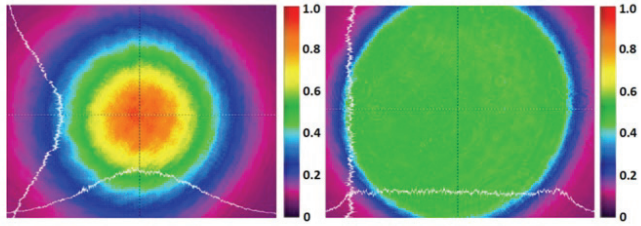

Figure 13. Experimental intensity profiles:
left – input TEM_{00},
right – flat-top π*Shaper* output.
(*Courtesy of NSYU, Taiwan*)

It was performed recording of hexagonal gratings using Gaussian and flat-top beams. To characterize the technology performance there were analyzed the size and shape of resulting dots in different regions of the sample marked in Fig. 14 by letters A, B, C, D and E. Microphotographs of dots in the said regions at the hexagonal grating are presented in Fig. 15, where upper raw of microphotographs corresponds to LIL using Gaussian beam, while the microphotographs of dots at the bottom are recorded using collimated flat-top beam.

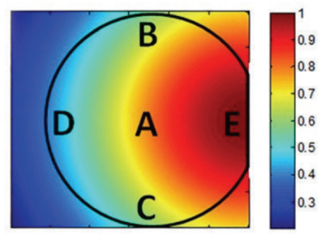

Figure 14. Layout of analysis zones.
(*Courtesy of NSYU, Taiwan*)

Difference in results of reproduction of the dots over the sample surface is evident:

- variable size and shape for Gaussian beam,
- stable size and shape when flat-top beam.

Thus, the basic approach to enhance performance of LIL technology by the use of field mapping beam shaper is experimentally confirmed. The article[14] contains more detailed evaluation of experimental results including statistics analysis with emphasize on the process characteristics important in semiconductor industry.

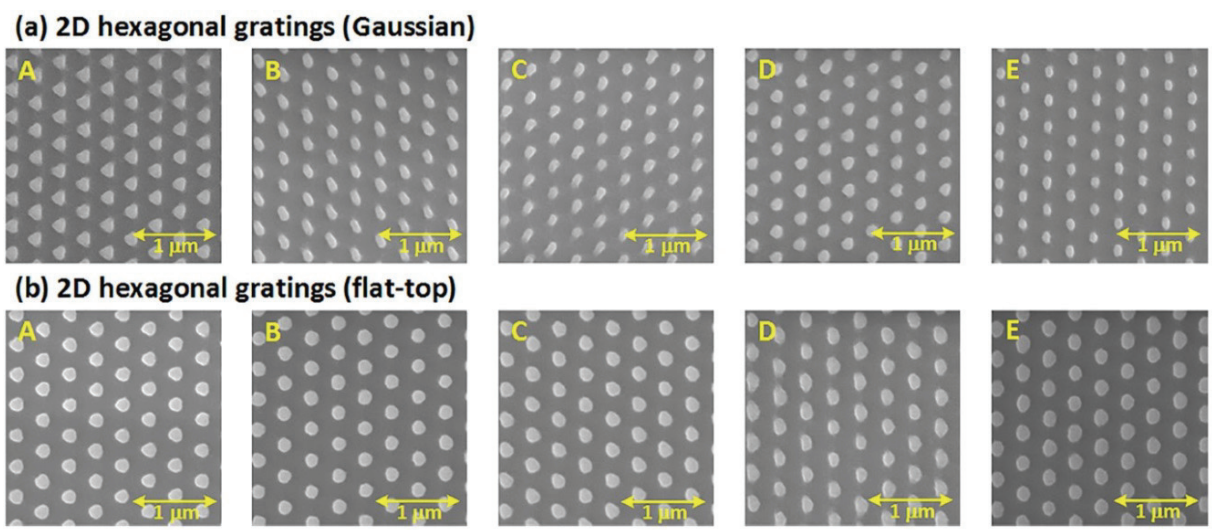

Figure 15. Microphotographs of 2D hexagonal gratings realized by employing (a) a Gaussian or (b) a flat-top light fields.
(*Courtesy of NSYU, Taiwan*)

5. CONCLUSION

Applying of refractive beam shapers πShaper in holography and interferometry applications makes it possible to provide two basic conditions of illumination with a laser beam: *flat-top irradiance profile and flat phase front*, which are mandatory ones in majority of holographic techniques and interference based technologies like Laser Interference Lithography or Volume Bragg Gratings recording. Those applications get essential benefits from laser beams of uniform irradiance: high contrast and equal brightness of reproduced images, stability of size and shape of reproduced periodic objects and patterns, higher process reliability and efficiency of laser energy usage, easier mathematical modelling. Optical systems for particular applications can be built on the base of field mapping beam shapers πShaper and telecentric imaging systems expanding capabilities of πShaper and allow creating image fields of practically unlimited size. Applying of spatial filtering with enlarged pinhole allows, simultaneously, providing irradiance uniformity of the *Image* field and suppressing of contrast or eliminating of parasitic patterns from small dust particles. Experimental researches and industrial practice confirm capabilities of this optical approach to enhance performance of interferometry and holography techniques.

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