Beam shaping to improve holography techniques based on Spatial Light Modulators

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ABSTRACT

Modern holographic techniques based on Spatial Light Modulators get serious benefits from providing uniform intensity distribution of a laser beam: more predictable and reliable operation, higher efficiency of laser energy usage, more simple mathematical description of diffraction transformations, etc. Conversion of Gaussian intensity distribution of TEM_{00} lasers to flattop one is successfully realized with refractive field mapping beam shapers like piShaper, which operational principle presumes transformation with high flatness of output wavefront, conserving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field, negligible residual wave aberration, and achromatic design provides capability to work with several laser sources with different wavelengths simultaneously. Applying of these beam shapers brings serious benefits to the Spatial Light Modulator based techniques like Computer Generated Holography, Dot-Matrix mastering of security holograms, holographic data storage.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in holographic systems. Examples of real implementations and experimental results will be presented as well.

Keywords: beam shaping, flattop, tophat, Spatial Light Modulator, Holography, CGH, homogenizing.

1. INTRODUCTION

Control of laser beam irradiance profile, particularly providing uniform distribution, is of great importance for various holography applications based on Spatial Light Modulators (SLM) like Liquid Crystal on Silicon or Deformable Mirror ones. A specific demand of SLM illumination in these 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 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 holography it is suggested to apply beam shaping systems built on the base of field mapping refractive beam shapers like *πShaper*, which operational principle implies almost lossless transformation of laser irradiance distribution from Gaussian to flattop, 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.

This article describes basic principles and important features of refractive beam shapers as well as some optical layouts that can be built on their base to meet requirements of modern laser technologies.

2. DESCRIPTION OF FIELD MAPPING REFRACTIVE BEAM SHAPERS

2.1 Basics of optical design

The design principles of refractive beam shapers of field mapping type, like *πShaper*, are well-known and described in the literature[1,5,6,7,8,9]. 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 a 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*.

Shortly the main features of refractive field mappers are:

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

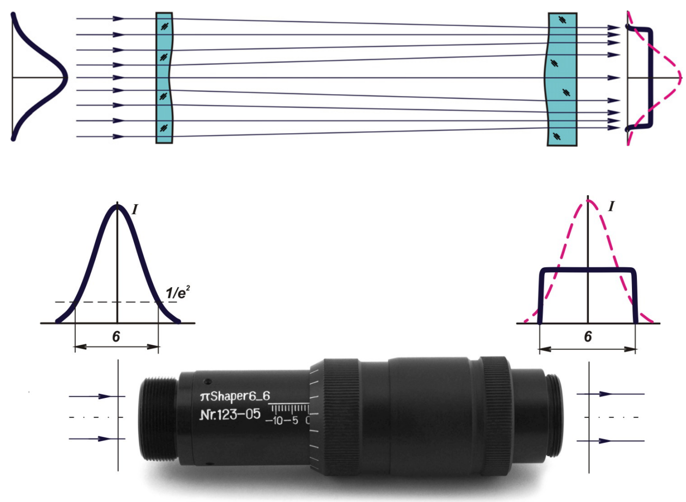

Figure 1 Refractive field mapping beam shaper *πShaper*

Example of beam shaping for 3rd Harmonic of Nd:YAG laser is presented in Fig.2.

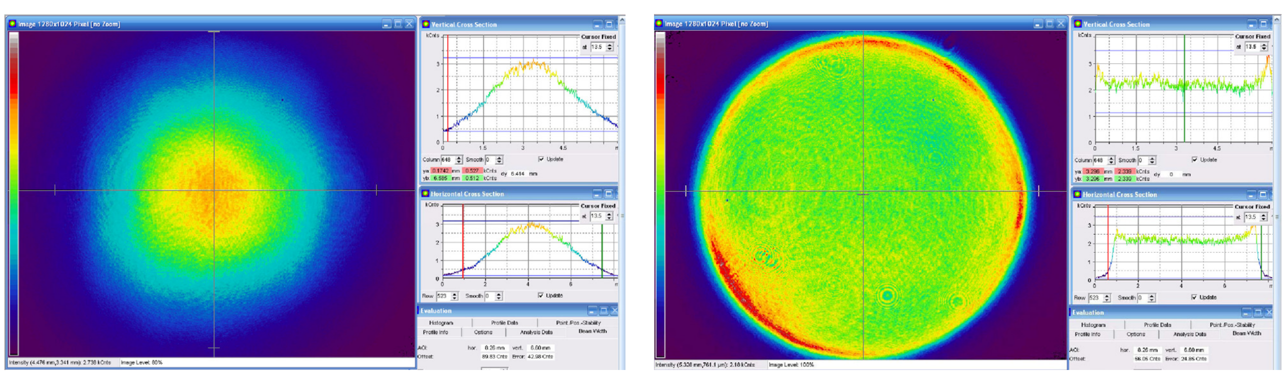
Figure 2 Example of beam shaping: Left – Input TEM_{00} beam, Right - after the *πShaper*
(Courtesy of Laser-Laboratorium Göttingen e.V.)

2.2 Adjustment features

Any beam shaping technique implies introduction of aberrations in a certain way and, therefore, requires fulfilment of some pre-determined conditions for proper transformation of a laser irradiance distribution. Like in other beam shaping techniques in case of refractive field mapping beam shapers it is necessary to take care for an input beam size, its irradiance profile and proper alignment of a beam shaper. These features were discussed in paper[10]. Here we can state that the requirements of beam shapers like *πShaper* are not tough, for example, alignment of a *πShaper 6_6* to be done with tolerances about 0.1 mm for lateral shift and about 10 arc minute for tilt, while the tolerance of input beam diameter is about 10%. Evidently, proper alignment of a *πShaper* can be done with using ordinary opto-mechanical alignment devices like 4-axis tilt/tip mounts, while the input beam size can be provided by widely used zoom beam expanders.

Another important feature of the beam shapers like *πShaper* is capability to compensate divergence/convergence of input beam through changing the air gap between components and easy adaptation to lasers with deviated from perfect Gaussian irradiance profile; all these features have great importance in practice.

2.3 Propagation of flattop 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, flattop 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 flattop 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[2,3,4], and is also a typical beam created by field mapping refractive beam shapers converting Gaussian to flattop laser beam.

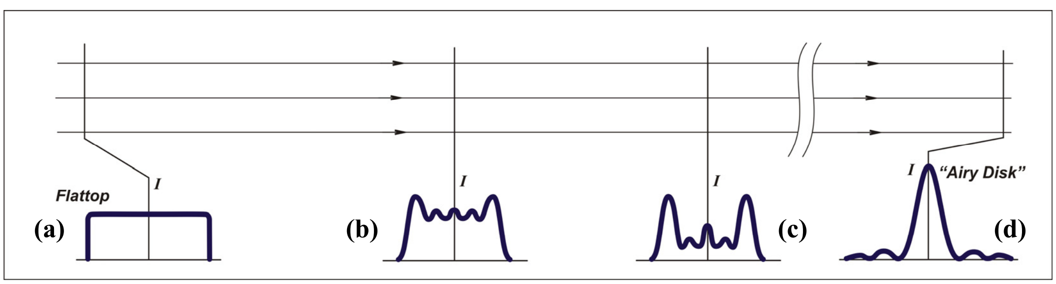

Figure 3 Irradiance profile variation by a flattop beam propagation.

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 "Airy disk" distribution described mathematically by formula

$$I(\rho) = I_0 \, [J_1(2\pi\rho)/(2\pi\rho)]^2 \qquad (1)$$

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

The "Airy disk" function is result of Fourier-Bessel transform for a circular beam of uniform initial irradiance[2,3]. Evidently, even a "pure" theoretical flattop 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 flattop beam diameter 6 mm after a *πShaper 6_6* the length where deviation from uniformity doesn't exceed ±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 various 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 flattop profile over extended DOF it is fruitful to apply imaging techniques that are considered in next chapter.

3. IMAGING OF FLATTOP 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 *πShaper*, essential features of this approach are considered in paper[12]. 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 holography to illuminate SLM with conserving the flatness of phase front and irradiance profile.

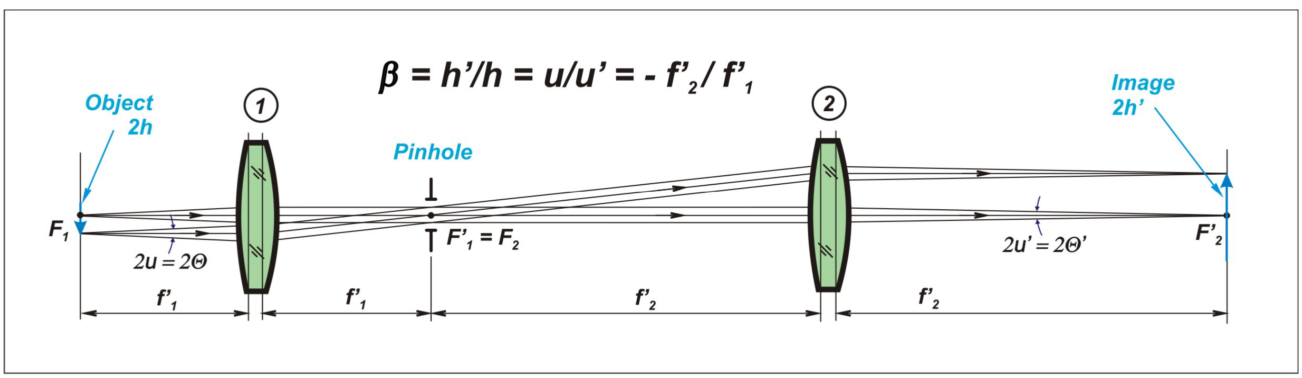

Figure 4 Telecentric imaging.

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 zero:

- 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 analyzed with using diffraction theory. Let's consider transformation of irradiance profile on example of the optical system to illuminate an SLM, Fig. 5.

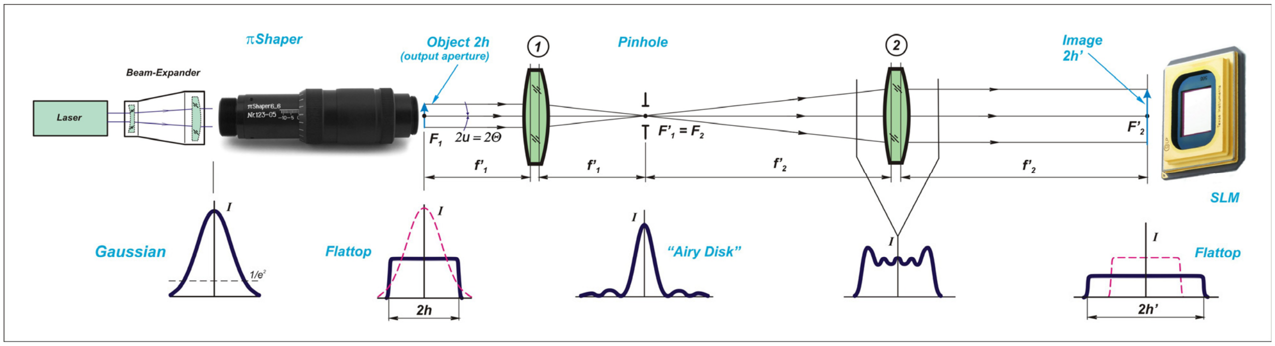

Figure 5 Layout to illuminate a Spatial Light Modulator.

Divergent Gaussian laser beam from TEM_{00} fiber coupled laser is transformed by the *πShaper* to collimated flattop beam, the output of the *πShaper* is considered as an *Object* plane for the telecentric imaging system. Since the *πShaper* 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. As result near the lenses, Fig. 5, 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. One of well-known conclusions of that theory is similarity of irradiance distribution in optically conjugated *Object* and *Image* planes[2,3]: *if the irradiance distribution is uniform in the Object plane, it is uniform in the Image plane as well*; and the profile at the *πShaper* output aperture will be repeated in the *Image* plane of that aperture, herewith the resulting spot size is defined by transverse magnification β. Evidently, if an SLM is located in the *Image* plane the incident radiation will be characterized by flat phase front and flattop intensity profile.

In the example in Fig. 5 the lenses are just singlets, but for high quality imaging more sophisticated optical systems should be applied, for example aplanats (with correction of spherical aberration and coma), microobjective lenses or other multi-component optical systems. Calculation of parameters of a particular imaging setup can be done with using well-known formulas of geometrical optics, described, for example, in book[4].

A positive lens has a well-known ability to perform two-dimensional Fourier transform[2,3] and create in its back focal plane irradiance distribution proportional to one in far field. This means in the considered case that irradiance distribution in back focal plane of 1st lens, marked in Fig. 5 as "$F'_1=F_2$", is just "Airy disk" described by formula (1).

Summarizing results of this example one can see that uniform irradiance after *πShaper*, 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*, sure, except the case of spatial filtering with using a pinhole that is considered in paragraph 3.3.

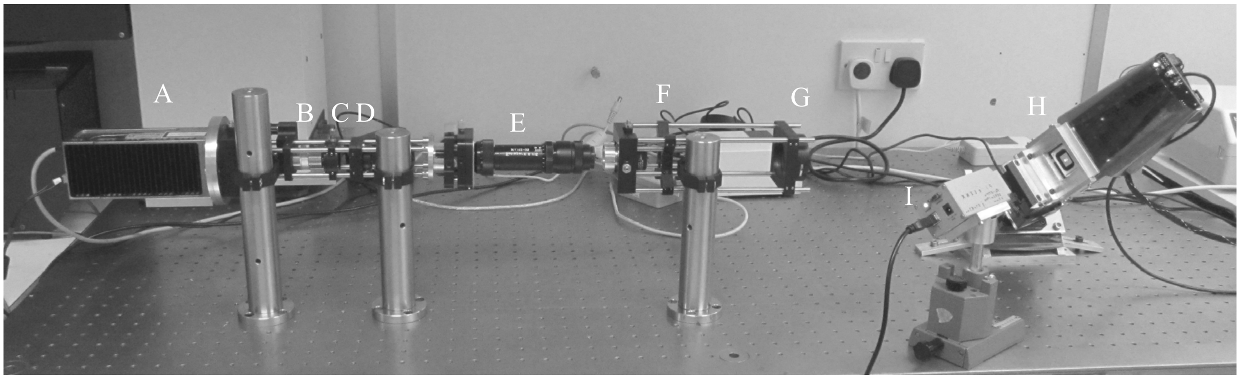

Figure 6 Experimental arrangement for illumination of DMD
A – Diode laser module (P_{max} = 110 mW, λ = 405 nm), B – microscope objective, C – pinhole, D – collimating lens, E – *πShaper 6_6*, F – lens, G – collimator, H – DMD (Texas Instruments 0.7" XGA 'DLP' chip, array size = 14x10.5 mm), note that the DMD is tilted over at a 45° angle so that the zero order image reflected from 'on' pixels propagates in the horizontal plane, I – image sensor.

Example of applying telecentric imaging optical system at the University of Sheffield[11] to illuminate the SLM in installation of Computer Generated Holography is shown in Fig. 6. A *πShaper 6_6_VIS* is used to reshape the beam from a laser diode so that a spatial light modulator (SLM), in the form of a Texas Instruments digital micromirror device (DMD), can be illuminated with a highly coherent, uniform-intensity beam. The DMD is used to project the images of computer-generated holograms that are used for research into photolithography on grossly non-planar substrates[13]. The same system can also be used to illuminate a liquid crystal on silicon (LCoS) SLM or to directly illuminate glass holographic masks. It is essential for these applications to maintain a controlled phase profile across the beam as well as achieving a uniform intensity profile. Initial laser source is the laser diode ($1/e^2$ diameter = 1.6 mm). This beam is spatially filtered using a microscope objective lens and a 25 µm diameter pinhole. The spatial filtering can alternatively be accomplished by coupling the laser output into a single-mode optical fiber. The beam is then recollimated using an achromatic doublet lens to produce a clean 5.9 mm diameter Gaussian beam (Fig. 5) for input into the *πShaper*. The *πShaper 6_6_VIS* has the achromatic optical design and is capable of working in the spectral band spanning 405 nm to 680 nm. The output from the *πShaper 6_6_VIS* is then further expanded by a 3.5x beam-expander to produce a 21 mm diameter flat top beam that is sufficiently large to illuminate the entire DMD (Fig. 6). A rectangular aperture close to the DMD can be used to avoid illumination of areas surrounding the micromirror array.

The optical system is used to project computer generated holographic images onto non-planar surfaces. Experimental results[13] demonstrated serious improvement of this technique by homogenizing of illumination of SLM, for example it has become possible to reproduce arbitrary locating in space light objects ob arbitrary shape and to realize the 3D-lithography.

3.3 Spatial Filtering

The spatial filtering[2] 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 spot 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[2,3]. 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 flattop beams the spatial filtering technique should be corrected through enlarging of pinhole diameter.

Let’s consider the layout in Fig. 5 where *πShaper* output is imaged onto an SLM with using 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 formula (1), then the uniform irradiance distribution is restored in the *Image* plane where SLM is locating. 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 *“Airy disk”* the restored in the *Image* plane irradiance distribution will be practically Gaussian but not uniform (flattop), 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 transmits through the pinhole, and not only “0” order central spot 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 with using formula (1) for conditions of a particular optical system. For example by focusing a laser beam of λ = 442 nm, uniform irradiance and 6 mm diameter with a perfect objective with focal length f’ = 50 mm, the 9 μm diameter pinhole would provide “usual” spatial filtering when only central “0” order spot is passed, while 120 μm diameter pinhole transmits almost 99% of energy, hence one can expect acceptable restoring of uniform irradiance distribution in *Image* plane (Fig. 5). Analysis of the irradiance distribution can be done by calculations on the base of the well known Fresnel-Kirchhoff diffraction integral[2,3], 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.

This software allows 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 presented irradiance profiles in the *Image* plane (Fig. 5) under condition of presence of a black opaque particle of Ø 0.05 mm (“dust”) in the *Object* and spatial filtering with using pinholes of various diameters. Evidently, contrast of the Ø 0.05 mm particle image is strongly suppressed and is practically negligible with Ø 0.2 mm pinhole. At the same time the resulting *Image* irradiance profile demonstrates good uniformity - deviation is approximately ±2%, that is acceptable in majority of applications.

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.

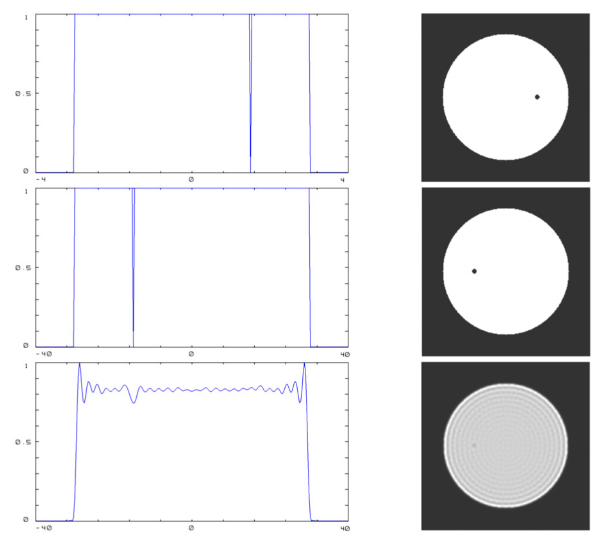

Figure 7 Profiles by spatial filtering of dust:
top- particle of Ø 0.05 mm on the *Object* (Fig. 6),
centre – *Image* when pinhole Ø 1 mm,
bottom - *Image* when pinhole Ø 0.2 mm.

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.

4. CONCLUSION

Applying of refractive beam shapers *πShaper* in SLM-based holography applications makes it possible to provide two basic conditions of the SLM illumination with a laser beam: *flattop irradiance profile and flat phase front*, which are mandatory ones for Computer-Generated Holography, Dot-Matrix hologram mastering, multi-colour Denisyuk holography, holographic data storage; these applications get essential benefits from homogenized laser beams: high contrast and equal brightness of reproduced images, higher process reliability and efficiency of laser energy usage, easier mathematical modelling. Availability for various wavelengths, achromatic design, implementations as telescopes and collimators, low divergence and extended DOF make the *πShaper* unique tools in building SLM-based holography systems. Telecentric imaging systems expand 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.

5. REFERENCES

[1] Dickey, F. M., Holswade, S. C., [Laser Beam Shaping: Theory and Techniques], Marcel Dekker, New York, (2000).

[2] Goodman, J.W. [Introduction to Fourier Optics], McGraw-Hill, New York, (1996).

[3] Born, M., Wolf E. [Principles of Optics], Cambridge University Press, Cambridge, (1999).

[4] Smith, W.J. [Modern Optical Engineering], McGraw-Hill, New York, (2000).

[5] Hoffnagle, J. A., Jefferson, C. M., "Design and performance of a refractive optical system that converts a Gaussian to a flattop beam", Appl. Opt., vol. 39, 5488-5499 (2000).

[6] Shealy, D.L., Hoffnagle, J.A., "Aspheric Optics for Laser Beam Shaping", [Encyclopedia of Optical Engineering], Taylor & Francis (2006).

[7] Kreuzer, J., US Patent 3,476,463, "Coherent light optical system yielding an output beam of desired intensity distribution at a desired equiphase surface", (1969).

[8] Laskin, A. "Achromatic refractive beam shaping optics for broad spectrum laser applications" Proc. SPIE 7430, Paper 7430-2 (2009).

[9] Laskin, A., US Patent 8,023,206, "Achromatic Optical System for Beam Shaping", (2011).

[10] Laskin, A., Laskin, V. "Variable beam shaping with using the same field mapping refractive beam shaper" Proc. SPIE 8236, Paper 82360D (2012).

[11] Laskin, A., Williams, G., McWilliam, R., Laskin, V. "Applying field mapping refractive beam shapers to improve holographic techniques" Proc. SPIE 8281, Paper 82810K (2012).

[12] Laskin, A., Laskin, V. "Imaging techniques with refractive beam shaping optics" Proc. SPIE 8490, Paper 8490-19 (2012).

[13] Maiden, A., McWilliam, R. P., Purvis, A., Johnson, S., Williams, G. L., Seed, N. L., Ivey, P. A., "Non-planar photolithography with computer generated holograms", Optics Letters, 30(11), 1300–1302 (2005).

6. ACKNOWLEDGEMENTS

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