BEAM SHAPING OPTICS TO IMPROVE HOLOGRAPHIC AND INTERFEROMETRIC NANOMANUFACTURING TECHNIQUES

Paper N405

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ABSTRACT

Abstract

Performance of various holographic and interferometric nanomanufacturing techniques can be essentially improved by homogenizing the intensity profile of the laser beam with using beam shaping optics like *πShaper* transforming the laser beam intensity from Gaussian to flattop one with high flatness of output wavefront, saving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field, negligible residual wave aberration. Applying of these beam shapers brings serious benefits to the Spatial Light Modulator based techniques like Computer Generated Holography, holographic projection processing applications, holographic lithography, interferometric techniques of recording the Volume Bragg Gratings. This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in holographic and interferometric systems. Examples of real implementations and comparative experimental results of applying the refractive beam shapers in systems of holographic lithography and other techniques.

Introduction

Various implementations of holographic and interferometric techniques applied in modern industrial applications of micromachining and nanomanufacturing use the Spatial Light Modulators (SLM) as versatile tools to control the laser radiation. 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, and in SLM-based applications this inhomogeneity of intensity is rather a source of problems: variation of brightness of reproduced images, instability of recording processes, reduced image contrast, inconvenience in realization of optical setups. Therefore, the task of transformation of laser beam intensity profile to a uniform one (flattop, tophat) is an actual task for SLM-based applications. For example, such SLM-based techniques like Computer Generated Holography (CGH) cannot be successfully realized without homogenizing of a laser beam applied. The optical task of converting an initial laser beam with Gaussian or similar intensity distribution to a flattop beam of low divergence is successfully solved by the refractive beam shapers of field mapping type[1,2,3,4,5] like *πShaper*. These beam shapers transform the beam profile with conserving the beam consistency and providing flat output wave front, so the output beam low divergence is the same like at the beam shaper entrance. This feature is very important for further manipulation of the resulting beam and makes it possible to realize various optical layouts like ones based on applying beam-expanders/reducers to vary the beam. Below we will consider some optical layouts incorporating *πShaper* and describe their features on the example of SLM-based CGH

Optical design considerations

The design principles of refractive beam shapers of the field mapping type are well-known and described in the literature[1,2,3,4,5]. Most often these devices are implemented as telescopic systems with two optical components, it is presumed the wave front at input and output are flat, the transformation of intensity profile from Gaussian to uniform one is realized in a controlled manner, by accurate inducing 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 intensity 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 beam profile without deterioration of the beam consistency and without increasing its divergence.

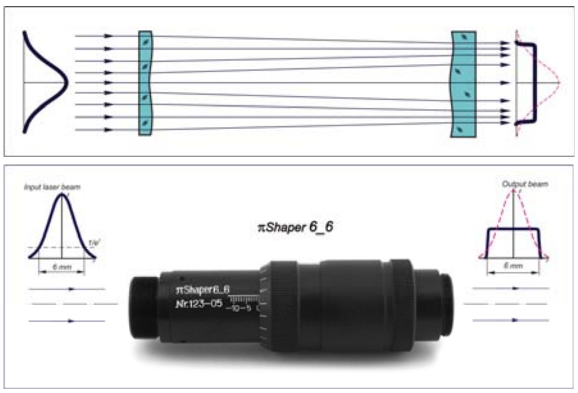

Figure 1 Refractive field mapping beam shaper *πShaper*

For the purpose of further considerations let us summarize main optical features of *πShaper* systems being used in this work:

- refractive optical systems transforming Gaussian, or close to Gaussian intensity distribution of source laser beam to a flattop (or top-hat, or uniform) one;
- transformation is realized through the phase profile manipulation in a controlled manner - accurate inducing by the first component of spherical aberrations to achieve the energy
- re-distribution and further compensation of the aberration by the second optical component;
- the output beam is free of aberration, the phase profile is maintained flat and low beam divergence is provided;
- TEM_{00} or multimode beams applied;
- collimated output beam,
- the resulting beam profile is kept stable over large distance;
- achromatic optical design, hence the beam shaping effect is provided for a certain spectral range simultaneously;
- Galilean design, no internal focusing.

Example of beam shaping for 3[rd] Harmonic of Nd:YAG laser with using *πShaper* is presented in Fig.2. Most often telescopic optical systems of refractive field mapping beam shapers are realized, hence the input and output beams are collimated. Due to design features the output divergence is approximately the same as that of the input beam.

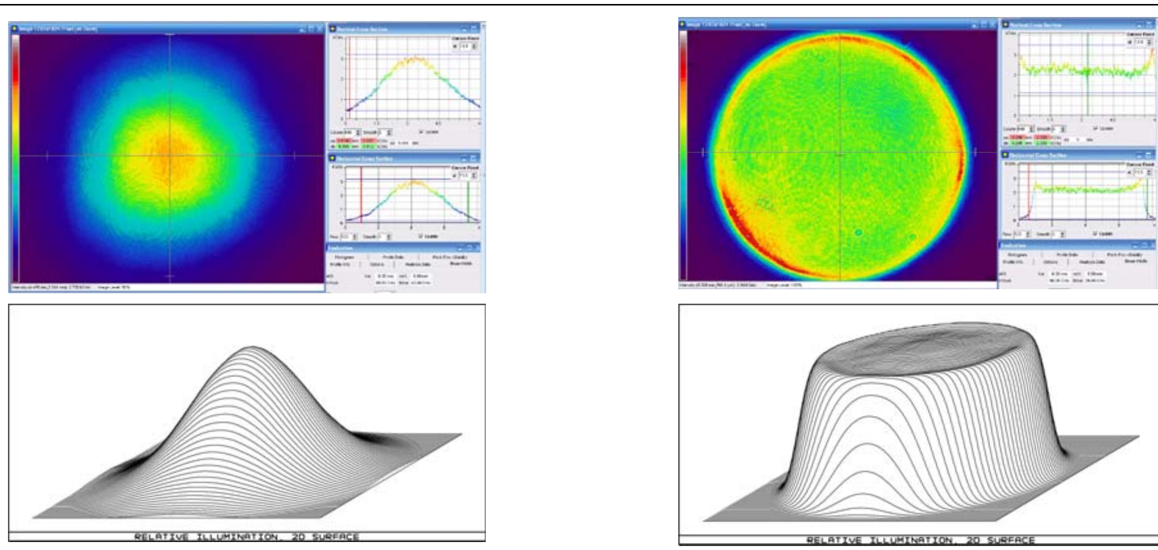

Fig. 2 Experimental and theoretical intensity profiles: Left – Input TEM_{00} beam, Right - after the *πShaper*
(Courtesy of Laser-Laboratorium Göttingen e.V.)

One can see also in Fig. 2 that the *πShaper* improves shape of a beam making it more regular and round, in certain sense the beam shaper works as a spatial filter.

One of basic design conditions for the *πShaper* systems is zero wave aberration – the flat input wave front is transformed to the flat output wave front. For proper operation in real applications, for example in industrial equipment, the beam shapers should provide certain tolerances for probable misalignments, like spatial shifts or tilts. Therefore, the real designs presume the same aberration correction level not only for the clear aperture of a system, but also in certain extent outside, typically for diameter at least 1.6 times larger than $1/e^2$ diameter of an input Gaussian beam.

By fine tuning the input beam size it is possible to adapt the *πShaper* to real laser beams with intensity distribution deviation from perfect Gaussian, for example, multimode beams with parabolic profiles or TEM_{00} beams with extended "wings".

The holographic and interferometric applications often require expansion of a beam after a *πShaper*, for example, to illuminate a SLM or a mask with a collimated laser beam of uniform intensity which sizes are larger than output beam diameter of a standard *πShaper*. This is an actual option in techniques like mastering of security holograms, Denisyuk holography, field illumination in Confocal Microscopes, interferometric techniques of recording the Volume Bragg Gratings and periodic structuring, holographic data storage and many others. At the same time, many scientific and industrial tasks can be successfully solved when a collimated beam of uniform intensity and diameter of about 1 mm is provided; some of them are laser welding, flow cytometry, mass spectrometry and different tasks of material processing.

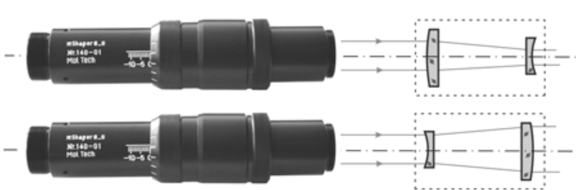

Fig. 3 Examples of reduction and expansion of a beam after the *πShaper* with using telescopic beam-expanders.

Common features of these beam transformations are varying the beam size and leaving the laser beam collimated. Evidently, this optical task can be easily solved by applying beam-expanders or beam-reducers of telescopic type with an appropriate magnification factor; the principle optical layouts are shown in Fig.3. Both Galilean and Keplerian telescopic systems can be applied. When a variable final beam size is required one can apply a zoom beam-expander.

In some interferometric applications it is strongly desirable to apply an expander of Keplerian type that is used as a telecentric imaging optical system: the output aperture of a *πShaper*, "Object", is located in front focal plane of the first telescope component, then the image will be created in back focal plane of the second telescope component. Example of this layout is shown in optical system presented in Fig. 4. Such a layout guarantees creating in image space extended zone with uniform intensity distribution and flat wave front – just these conditions are optimum for realization of any interferometric technique.

Optical layout of SLM-based CGH

Description

Let's consider the optical layout for Computer Generated Holography on the base of *πShaper 6_6* realized at the University of Sheffield[6] to reshape the beam from a laser diode so that a spatial light modulator, 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[7]. 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. Only field mapping beam shapers like the *πShaper* solve this task successfully and fulfill these conditions simultaneously.

The optical system for the DMD illumination is shown in Fig. 4 and measured intensity distributions in Fig. 5. Input to the system is the distorted TEM_{00} (Gaussian) beam from the laser ($1/e^2$ diameter = 1.6 mm). This beam is spatially filtered using a microscope objective lens and a 25 µm diameter

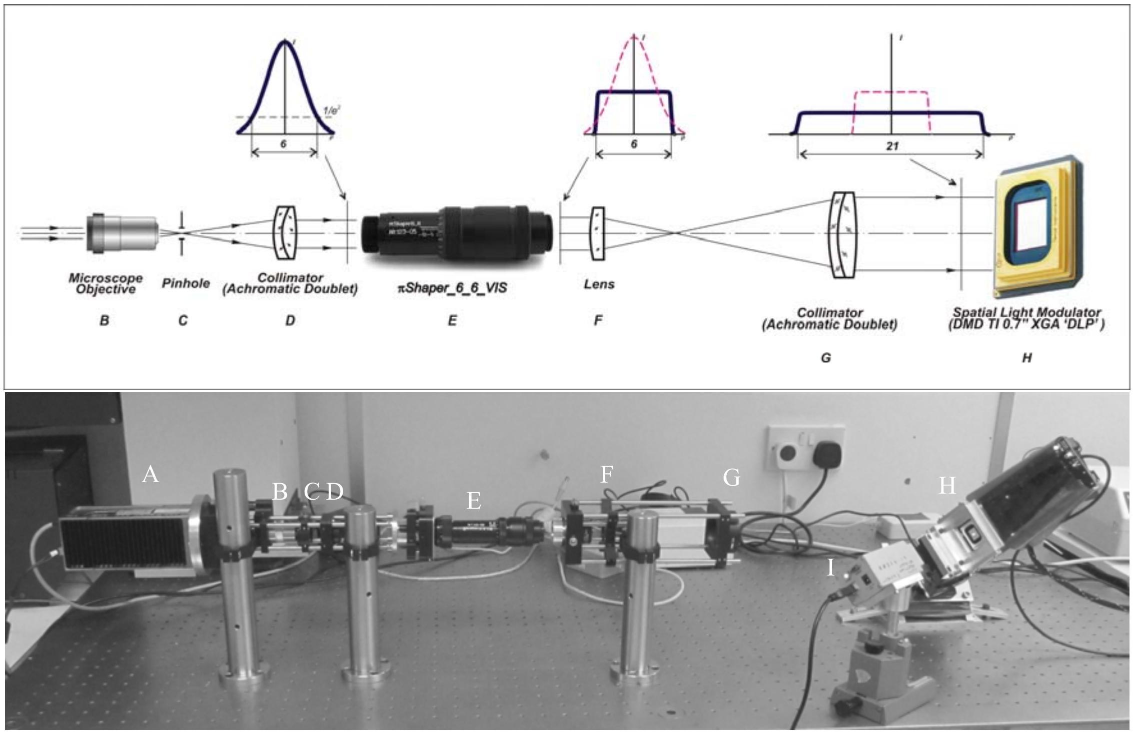

Figure 4 Experimental arrangement for illumination of DMD

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.

pinhole. The spatial filtering can alternatively be accomplished by coupling the laser output into a single-mode optical fibre. The beam is then recollimated using an achromatic doublet lens to produce a clean 6 mm diameter Gaussian beam (Fig. 5a) for input into the *πShaper*. The *πShaper 6_6* has achromatic optical design and is capable of working in the spectral band spanning 405 to 680 nm.

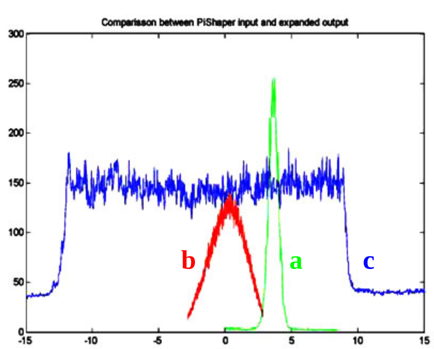

Fig. 5 Beam profiles: a) laser output,
b) *πShaper* input,
c) final expanded DMD input

The output from the *πShaper 6_6* is then further expanded by a 3.5x beam-expander to produce a 21 mm diameter flat top collimated beam that is sufficiently large to illuminate the entire DMD (Fig. 5c). Here just the telecentric imaging system in form of Keplerian telescope is applied. The final spot illuminating the DMD is shown in Fig. 6. A rectangular aperture close to the DMD can be used to avoid illumination of areas surrounding the micromirror array.

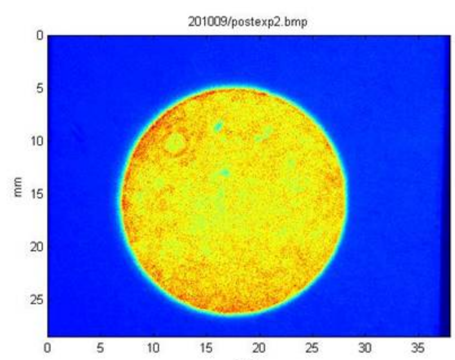

Fig. 6 Final expanded laser beam, at DMD.

By expansion of the beam after the *πShaper* the divergence is reduced in proportion to the magnification, thus giving the final expanded flattop beam a greatly extended depth of field. This simplifies the integration of the system with the DMD.

Experimental results

The optical system is used to project holographic images onto non-planar surfaces. Pre-coating the surfaces with a photoresist then enables non-planar lithography to be performed[7]. The simplest computer-generated holograms are based on a Fresnel zone plate representation of a cylindrical lens. For instance the pattern in Fig. 7 produces a line-in-space 20 cm from the DMD, see profiles in Fig. 8

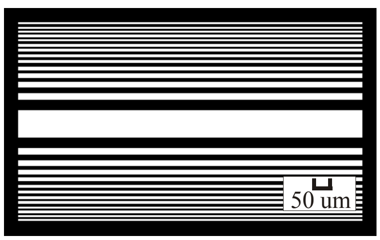

Fig. 7 Computer-generated hologram for projection using DMD - Line-in-space 20 cm from DMD

If the DMD is illuminated without including the *πShaper* in the optical system, then there is a Gaussian intensity distribution across the image, Fig. 8, top.

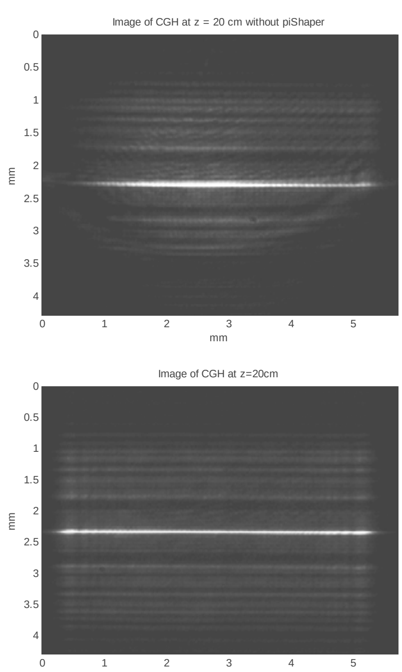

Fig. 8 Camera images produced by CGH on DMD
Top - without and Bottom - with *πShaper*

The intensity variation can be reduced by expanding the beam so that just the central portion of the Gaussian is used, but this means losing most of the available power from the laser and hence greatly increasing the photoresist exposure time. For lithographic applications it is necessary to have no more than a few percent intensity variation across the field. For instance, allowing a maximum 5% intensity variation implies losing 65% of the available laser power. The image produced by the CGH shows marked intensity variation (Fig. 8, top), this unsuitable for photolithographic purposes. By contrast, the image produced by the same CGH when the *πShaper*

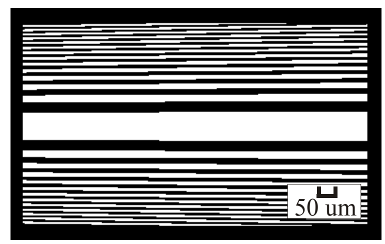

Fig. 9 Computer-generated hologram for projection - sloping line between 20 and 22 cm from DMD

is included is shown in Fig. 8, bottom. This image shows near-uniform intensity along the line.

In general the main idea of that holographic lithography technique is to generate arbitrary locating

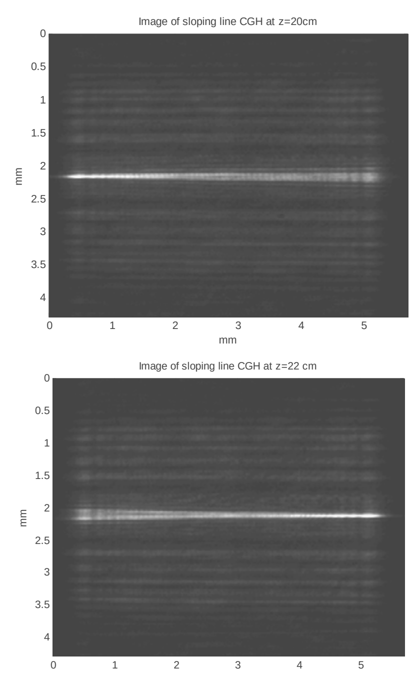

Fig. 10 Images of sloping line CGH at
Top - 20 cm and Bottom - 22 cm from DMD

in space light objects by varying the pattern of the hologram. A simple example of such an object can be a sloping line, it can be generated by the CGH with a gradually increasing fringe spacing (Fig. 9).

Fig. 10, top shows the left end of the line in focus, whilst Fig. 10, bottom shows the right end of the line in focus. It is very good seen that the ends of the tilted Line are sharp, this means very good reproduction of that light object.

Evidently, these results couldn't be achieved with using an ordinary Gaussian beam.

The uniform intensity of laser beam provided by the *πShaper* brings flexibility in this CGH-technique and lets it possible to generate light objects of arbitrary shape and location in space.

Conclusions

Applying of refractive beam shaping optics of field mapping type in SLM-based optical systems of holography or interferometry applications makes it possible to provide two basic features of illuminating laser radiation: flattop intensity distribution and flatness of wave front. These features are mandatory conditions for any SLM-based laser technique: Computer-Generated Holography, Dot-Matrix mastering the security holograms, multi-colour Denisyuk holography, holographic data storage, confocal microscopy, as well as for interferometric techniques of recording the Volume Bragg Gratings and periodic structuring. These applications get essential benefits from using homogenized laser beams in sense of contrast and equal brightness of reproduced images, higher process reliability and efficiency of using the laser radiation, easier mathematical modelling. Availability of beam shapers for various laser wavelengths, achromatic design, low divergence and extended depth of field of flattop beam, easy manipulation of resulting beam size and shape make the *πShaper* a unique tool to improve holographic and interferometric nano- and micromanufacturing technologies.

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Acknowledgement

Authors are thankful to *πShaper* users in University of Sheffield, Laser-Laboratorium Göttingen for their active and patient work with *πShaper* and kind permission to publish some results of experiments.