DIAMOND FOCUSATORS FOR FAR IR LASERS

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Recently a new technique has been proposed for laser-assisted generation of phase microrelief to manufacture diamond diffractive lenses for the far IR range. In the present paper the realization of diamond diffractive optical elements (DOEs) is considered, able to focus an incoming CO_2 laser beam into certain pre-given focal domains. Exemplarily, two completely different DOEs for different tasks of laser beam focusing have been designed by different methods, manufactured and finally investigated by means of optical experiment and computer simulation. Measured intensity distributions in the DOEs' focal planes as well as measured diffraction efficiencies have been compared with related results of computer simulation, and have been found to be in good mutual concordance. Obtained first results indicate that technique of laser-assisted ablation can be effectively used for manufacturing of high quality diamond DOEs for laser beam focusing.

Keywords: diamond diffractive optical elements, CVD diamond, UV laser ablation, surface micro-patterning, CO_2 laser optics

1. Introduction

The application of diamond-based optical elements for high-power CO_2 lasers is of particular interest because of the low optical absorption coefficient of this material in combination with it's very high thermal conductivity and the weak temperature dependence of refractive index [1,2]. Recent advances in gas-phase synthesis have made it possible to fabricate polycrystalline CVD diamond films whose optical and thermal properties are close to those of single crystal diamond material, whereas they are far cheaper. As a result, these sophisticated materials are applied more and more to tasks dominated till now by other materials. One example for this are windows for high-power CO_2 lasers in the 5 – 20 kW domain. In Table 1 the most relevant parameters of CVD diamond regarding this application are compared with those of ZnSe, a frequently used till now material for such windows.

Table 1.

Parameter	*CVD-diamond*	*ZnSe*
Thermal conductivity at 300 K, (W/cm K)	18-20	0.16
Absorption at 10.6 μm (1/cm)	$5*10^{-2}$	$5*10^{-4}$
Hardness (GPa)	81±18	1.05
Thermal expansion coefficient at 300K (ppm/K)	1.0	7.1
dn/dT (1/K)	$9.6*10^{-6}$	$57*10^{-6}$

It would be very attractive to use CVD diamond material not only for windows, but additionally for elements with an optical power. Since the physical sizes of the free-standing CVD diamond films are limited actually to a thickness $\leq$ 2 mm and an area ≤ 100 cm^2, realization as conventional optical lenses is impossible.

As a way out, the use of flat diamond diffractive optical elements (DOE) has been proposed [3], following the basic approaches in the design and fabrication of DOEs with conventional IR materials [4]. To realize this idea, a method of selected-area laser ablation has been applied to produce diffractive microrelief at the surface of an optical element. A similar technique has been used successfully to generate subwavelength periodic microstructures on top of a diamond film to modify its reflectivity [5,6]. The efficiency of this approach was recently demonstrated by realization and investigation of diffractive cylindrical and Fresnel lenses from CVD diamond [3,7].

Main goal of the present study is to show that diffractive optical elements with more complex relief topology can be produced from CVD diamond plates using the laser ablation process as well. For instance, DOEs capable to focus the beam of high-power CO_2-lasers into pre-given complex focal domains (so called "focusators") are of actual practical interest.

2. Design of diamond DOEs for IR laser beam focusing: formulation of the problem

Let's consider the task of DOE design for focusing an input laser beam into a pre-given two-dimensional domain (Fig.1.).

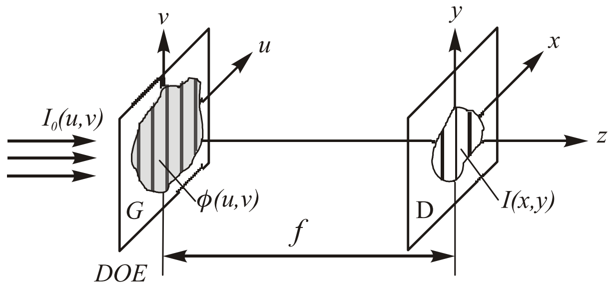

Fig. 1. Principle of laser beam focusing by DOE

Knowing intensity distribution $I_0(u,v)$ and phase distribution $\phi_0(u,v)$ in the cross-section of illuminating beam and intensity distribution $I(x,y)$ to be formed inside focal domain D, this task can be reduced to the search for a proper phase function of the DOE.

In the present paper, we report on the design, fabrication and testing of two different types of CVD diamond DOEs focusing a laser beam into different pre-given domains. Firstly, a DOE focusing a Gaussian beam into a homogeneously filled focal rectangle ("Gauss-to-rectangle" focusator) was calculated by a ray-tracing approach discussed in [4]. Secondly, a DOE focusing a Gaussian beam into a focal square contour ("Gauss-to-square contour" focusator) was calculated, exploiting an adaptive iterative procedure described in [8]. Both elements were designed and fabricated to operate at the CO_2 laser wavelength (λ=10.6 µm). All numerical calculations of the diffractive surface profile were made for an illuminating beam described by a Gaussian intensity distribution

$$I_0(\mathbf{u}) = C\exp\left(-\frac{2\mathbf{u}^2}{\sigma^2}\right), \qquad (1)$$

where **u**=(u,v), and a phase distribution according to $\varphi_0(\mathbf{u}) = const.$

3. Computer design of diamond DOEs

Relevant parameters of both designed diffractive elements are presented in Table 1.

The lateral discretization step respectively pixel size was chosen as s=40µm*40µm (which is nearly 4λ*4λ) as a compromise between diffractive scalar theory demands [9] and technological considerations. The number of phase quantization levels M=8 was selected from technological considerations as well as from intention to approximate the designed continuos phase function of DOEs as good as possible.

Table 2.

	"Gauss-to-rectangle" focusator	***"Gauss-to-square contour" focusator***
Focal length, *f*	100 mm	100 mm
Operating wavelength, λ	10.6 µm	10.6 µm
Number of phase quantization levels, M	8	8
Aperture, *G*	6.64 mm × 6.64 mm	6.64 mm × 6.64 mm
Pixel size, s	40 µm x 40 µm	40 µm x 40 µm
Focal domain, *D*	Homogeneously filled rectangle, 1.75 mm×3.5 mm	Square like line contour, 4.2 mm x 4.2 mm, line thickness 0.4 mm.
Illuminating beam radius, σ	1.85 mm	1.85 mm
Refractive index of substrate (CVD diamond), n	2.4	2.4
Maximum depth of microrelief, $h_{\max} = \frac{\lambda}{(n-1)}$	7.57 µm	7.57 µm
Calculated efficiency*, η	68.7 %	51.8 %
Method of calculation	Geometrical optics	Adaptive iterative procedure (35 iterations)

*including Fresnel losses, which are about 30% for two diamond-air interfaces

Calculated 8-level phase distributions for the two investigated elements are displayed in Figures 2a and 2b. Both DOEs are "Fresnel elements", which means that a lenslike phase function has been included into the focusators' phase function.

Intensity distributions obtained by "simulated illumination" of the calculated elements (two-dimensional FFT algorithm with 256 x 256 pixels) are displayed in Figures 3a and 3b.

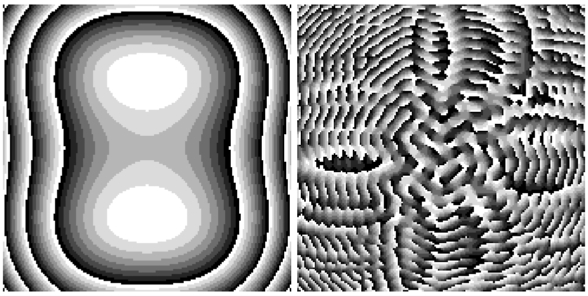

Fig. 2. Phase masks of calculated DOEs: (a) Gauss-to-rectangle focusator, (b) Gauss-to-square contour focusator.

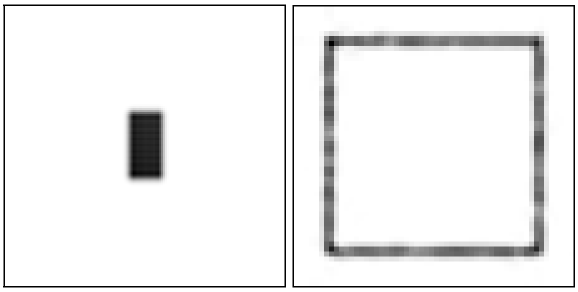

Fig. 3. Computer-simulated intensity distribution in the focal plane (with different magnification): (a) Gauss-to-rectangle focusator, (b) Gauss-to-square contour focusator.

To estimate the focusing quality, the energy efficiency

$$\eta = \int_D I(\mathbf{x}) d^2\mathbf{x} \, / \int_G I_0(\mathbf{u}) d^2\mathbf{u}\,, \qquad (2)$$

was used, which characterizes the portion of illuminating beam's energy focused into the desired focal domain *D*, where $I(\mathbf{x})$ is the focal intensity distribution and $I_0(\mathbf{u})$ is the illuminating beam's intensity distribution.

To manufacture the calculated elements, achieved 8-level phase distributions had to be transferred into corresponding etching-depth profiles.

4. Diffractive surface relief generation by laser ablation

Diamond films with a thickness of 300-400 µm were grown on polished Si substrates by a microwave plasma CVD technique using an ASTeX CVD diamond reactor (Model ASTeX-PDS19, 5 kW power, 2.45 GHz frequency) [10]. After separation from the substrates, resulting free-standing diamond films were cut into pieces of about 1 cm^2 size by laser cutting, polished, and then were used for laser patterning experiments. Micro patterning of the surface was performed with a KrF excimer laser (model EMG 1003i "Lambda Physik", 248 nm wavelength, 15 ns pulse duration, energy per pulse ~200 mJ) in an optical projection scheme with a linear demagnification of 1:10. This set-up is shown in Fig. 4. schematically.

Resulting profile depth could be modified by variation of energy density and number of laser pulses. As an example, in Fig. 5. the achieved etching rate is depicted in dependence of the KrF laser's fluence effective for an image size of 40µm*40µm at the sample surface.

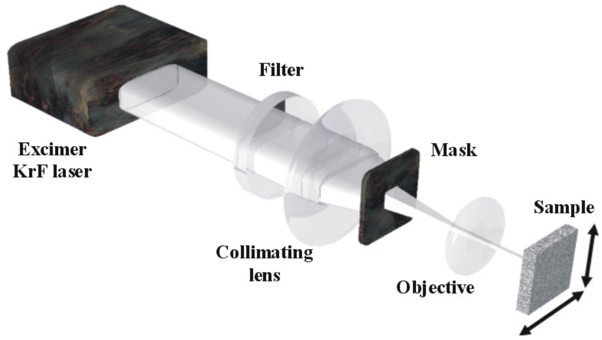

Fig. 4. Optical projection scheme with the KrF excimer laser.

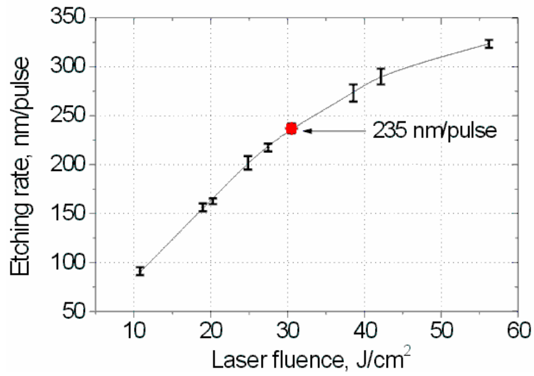

*Fig. 5. Etching rate as function of the KrF laser's fluence effective for an image size of 40µm*40µm at the diamond sample surface*

A typical detail of the realized diffractive microrelief is depicted in Fig. 6. Note that specific „borders effects" occur between neighboring pixels as result of different character of interaction of UV radiation with diamond material at the borders of illuminated square-like spot and in its central part. It can be assumed that light diffraction at these borders will not give significant contributions to the focal image because feature size is smaller than wavelength. However, such effect can lead to certain decreasing of DOE diffractive efficiency.

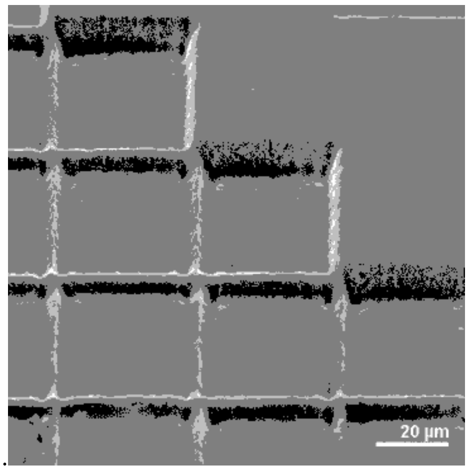

Fig. 6. A typical detail of the realized 8-level diffractive microrelief.

5. Experimental setup for the optical investigation of DOEs

The setup used for experimental investigation of the field formed by fabricated diamond DOE as well as of the incoming beam is schematically shown in Fig. 7. The main components are a 5-W CO_2 laser (single-mode TEM_{00}) with a divergence of 3.84 mrad (full angle) and a beam-waist radius σ=1.85 mm, and an IR camera with 120 x 120 pixels, a pixel size of 100 µm, and an 8-bit intensity resolution. The experimental determination of the diffraction efficiency (setup of Fig. 7, too) was realized when the camera was replaced by the head of a power meter.

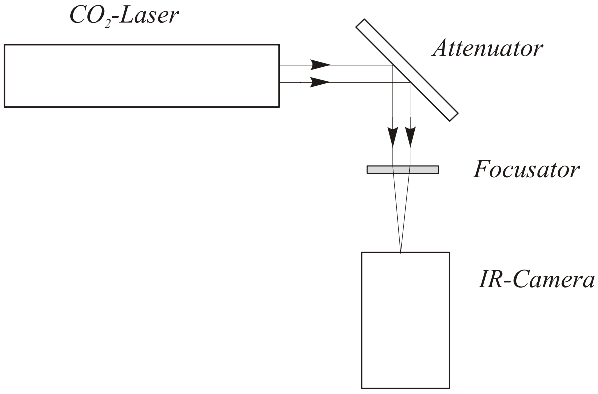

Fig. 7. Experimental setup for the investigation of formed intensity distribution and of diffraction efficiency.

6. Experimental results and their comparison with theoretical calculations

The structure of the generated beams as seen by IR camera in focal plane is illustrated in Fig. 8 and Fig. 9.

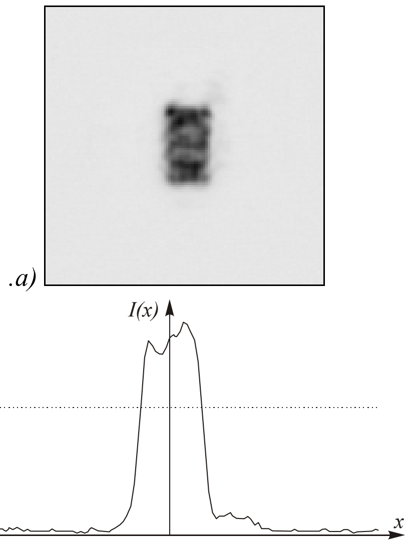

Fig. 8. Measured intensity in the focal plane of "Gauss-to-rectangle" focusator (a) and corresponding sectional view through center (b).

Comparing Fig. 9 with corresponding simulation results (Fig. 10) manifests a very good correspondence regarding the formed intensity distribution (note that results given with different magnification).

Comparing measured intensity distribution formed by the "Gauss-to-rectangle" focusator (Fig. 8) with related results of computer simulation, certain deviations become evident. This deviation can be explained by technological errors connected with instability of applied UV laser during ablation process.

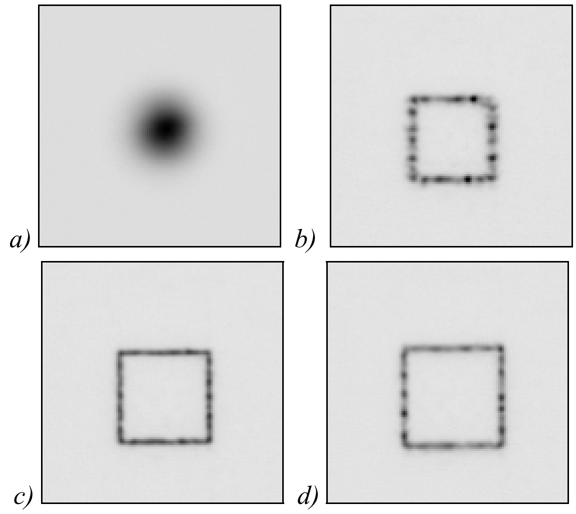

Fig. 9. Experimentally measured intensity distribution in the cross-section of illuminating beam (a) and for different cross sections of the formed beam ("Gauss-to-square contour" focusator): (b) z = 90 mm, (c) z = f= 100 mm, (d) z = 110 mm.

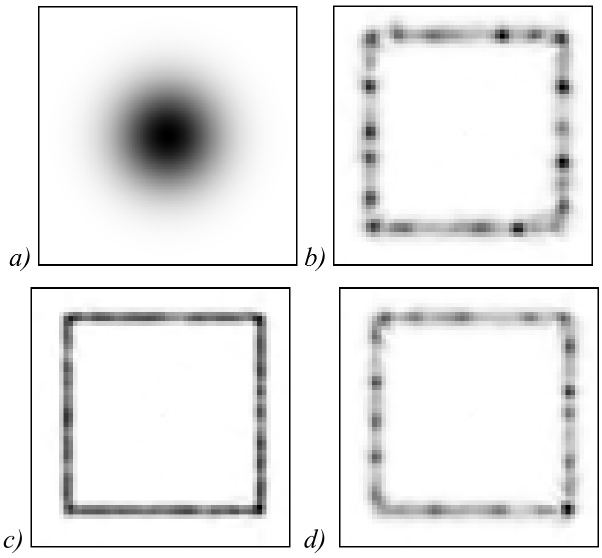

Fig.10. Computer-simulated intensity distribution in the cross-section of illuminating beam (a) and for different cross sections of the focused beam: (b) z = 90 mm, (c) z = f = 100 mm, (d) z = 110 mm.

The measured energy efficiency in this experiment was found to be η = 54% for the "Gauss-to-rectangle" focusator and η = 42.5% for "Gauss-to-square contour" focusator, which is somewhat less than the theoretical estimations mentioned in Table 2. This difference may be accounted for by influence of "border effect" between neighboring pixels, mentioned above, and by further technological imperfections.

7. Conclusion

CVD diamond based diffractive optical elements with complex relief topology capable to focus the beam of CO_2-lasers into pre-given complex focal domains ("focusators") have been fabricated by laser patterning. The correlation between the experimental characteristics of the DOEs and the results of numerical simulation suggests that the laser processing provides an adequate accuracy for the formation of the surface microrelief. Thus, our investigations have shown that a laser ablation technique is a promising method for manufacturing of high quality multilevel diamond diffractive elements for laser beam focusing.

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