Design of diffractive optical elements for CO_2-laser material processing

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Abstract

In this paper we report on the design of diffractive optical elements (DOEs) for high power laser radiation. We modified the Fourier transform algorithm, which allows hologram calculation also for reflective type Kinoforms considering the tilted arrangement. To achieve light weighted DOEs which are resistend against intense laser radiation reflective DOEs in silicon were fabricated. The elements have been investigated with respect to the diffraction efficiency and the absorption values.

1 Introduction

Diffractive optical elements (DOEs) are usefull for many applications in modern optics. One of them is laser material processing with high-power CO_2-laser at a wavelength of 10.6 μm. In this case DOEs can be used for cutting, marking, tempering, drilling and welding. The advantage of DOEs compared with refractive elements are their flexibility for wavefront reconstruction[1]. DOEs might become key devices for laser processing, since they allow to generate arbitrary beam profiles or intensity distribution at the workpiece. Thus they provide a key element for laser material processing without scanning mirrors. For CO_2-laser material processing the DOEs should accomplish several requirements. First they should be designed as reflective type elements with low absorption, because they are better to cool than refractive transmission optics. Furthermore the DOEs should be realized as Kinoforms in order to achieve high diffraction efficiency and to avoid energy losses.

2 Design of reflective DOEs

Recently some authors reported about the design and application of DOEs for CO_2-lasers where the diffraction patterns were calculated with ray-traycing methods [2] [3]. For many applications those elements are very sensitive to a change of the input beam profile (mode structure), since the DOE performs a geometrical mapping from the input (position of

the DOE)- to an output plane (position of the workpiece). This might lead to severe distortions in the output beam profile. Fourier holograms do not suffer from this drawback. Furthermore, iterative Fourier algorithms (IFTA) are convenient and powerful methods and they allow a flexible element design [4]. The approach was adapted to an inclined incident illumination of the hologram. After the calculation the continuous phasefunction was encoded in a binary Kinoform.
Usually if one is using Fouriertransform algorithms to calculate a DOE-pattern, it is assumed that DOE- and reconstruction plane are perpendicular to the optical axis. For the case considered here (reflecting type DOE) the hologram is tilted along the x-axis by 45° (Fig. 1).

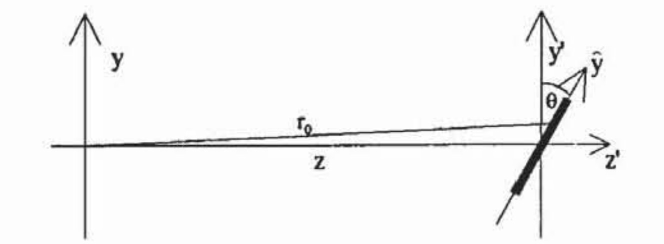

Fig. 1: Schematic illustration of the coordinate system in the hologram plane for the tilted $(\hat{x}, \hat{y})$ and untilted case (x', y')

To get the phase function for the inclined direction of illumination the process of calculation is divided in two steps. In the first step the DOE's phase function is evaluated for perpendicular illumination. In the second step the phase function is modified for the inclinded illumination.
The procedure in detail is as follows: First, the data of the desired light distribution to be reconstructed (for our case here it is a ring) are feed into a computer. Superimposed is a random phase to yield the final input for the iterative calculation procedure. Within each iteration loop complex amplitude values are Fourier–transformed between the hologram- and the reconstruction plane. Each time the magnitude of the hologram function is set to a constant value, while in the reconstruction plane the magnitude is replaced by its predefined values (e.g. the ring pattern). The corresponding phase functions of every Fourier transform are maintained. The aim of this procedure is to minimize the deviations between the predefined light distribution and the resulting pattern, attained by the computer simulated reconstruction. Deviations arise since only the phasefunction in the hologram plane is used and the amplitude is neglected. (Kinoform has a pure phase transmittance). Typically 150 iteration loops were applied. The resulting phase function has to be modified for the case of an inclined illumination. Since the coordinate system of an untilted DOE is distorted in comparison to the tilted DOE given by:

$$\frac{x'}{\lambda z} = f_x = \frac{\hat{x}}{\lambda r_0}; \qquad \frac{y'}{\lambda z} = f_y = \frac{\hat{y}\cos(\theta)}{\lambda r_0} \tag{1}$$

$$r_0 = \sqrt{z^2 + \hat{x}^2 + \hat{y}^2 + 2\hat{y}z\sin(\theta)} \tag{2}$$

where f_x, f_y denote the spacial frequencies in the DOE-plane, while x', y' describe the coordinates in the untilted plane [5]; z denotes the distance between the hologram- and the reconstruction plane, θ is the tilt angel. The mapping of the sampling grid from the untilted (x', y') to the tilted $(\hat{x},\hat{y})$ DOE-plane is given by :

$$\hat{x}(x', y') \;\; and \;\; \hat{y}(x', y') \tag{3}$$

and is schematically shown in Fig. 2.

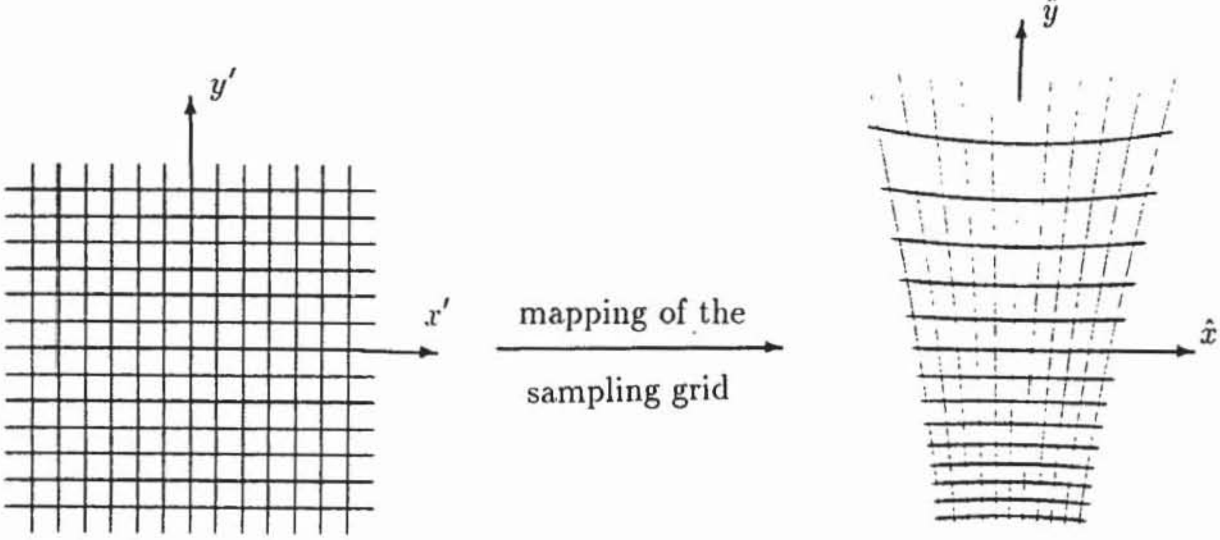

Fig. 2: Scheme of the rectangular (perpendicular illumination) and the distorted coordinate system (inclined illumination)

Consequently the phasefunction of the untilted DOE has to be projected to the distorted coordinate system. That is, we have to interpolate the original phasefunction onto the distorted sampling grid. Instead of the more accurate sinc-interpolation we use a linear interpolation because there is less computation time.
The DOE consists of a 4096 * 5792 pixels and is calculated for $z = 1m$. The nummerical calculation was carried out on an IBM compatible personal computer with a 80386/387 CPU.

3 Fabrication procedure of reflective DOEs

For our investigations light weight DOEs are of interest, suitable for moving parts (e. g. in a roboter system). We chose Silicon as substrate material, since it has a relative low mass density (2.40 gcm^{-3}), high specific heat (0.737 $Jg^{-1}K^{-1}$) with moderate thermal conductivity (1.56 $Wcm^{-1}K^{-1}$) and low linear thermal expansion (2.56 10^{-6} K^{-1}) in comparision to Copper (corresponding values are: 8.96 gcm^{-3}, 0.386 $Jg^{-1}K^{-1}$, 3.90 $Wcm^{-1}K^{-1}$, 16.6 10^{-6} K^{-1}) [6]. Moreover the parameters for etching the DOE pattern in Silicon are well known from elctronic circuit technology.

For the exposure of the hologram-masks (KODAK High Resolution plates 1A) we use a laser-scanner with minimal spotsize of less than 1 μm ($\lambda = 454\ nm, NA = 0.9$) and a position accuracy of 0.5 μm. The binary amplitude mask is contact copied in a resist coated Silicon substrat (see Fig. 3) using a standard UV-resist exposure system. The resulting DOE relief pattern in the photoresist layer is transferred in a silicon substrate by reactive ion etching (CF_4/SF_6 gas-mixture is used, 140 W HF-power, etching time: 30min).

If incident and reflective angle θ are equal, the depth of the relief d is given by:

$$d = \frac{\lambda\ \Delta\phi}{2\pi cos(\theta)}; \tag{4}$$

where $\Delta\phi$ is the phase shift caused by the surface profile.

For binary holograms $\Delta\phi = \pi$. With $\lambda = 10.6\ \mu m$ and $\theta = 45°$ the etched depth value in silicon amounts to $d = 3.75\ \mu m$. The tolerance on the depth we obtained was $\pm 15\ nm$. Finally, silicon is coated with a high conductive layer (e. g. gold), nessecary for high reflectivity.

4 Diffraction efficiency and absorption measurements

The diffraction efficiency for the binary DOE was evaluated by computer simulation as well as experimentally in an optical reconstruction setup. In the case of a ring shaped light distribution (Fig. 3), where the -1st and +1st order are used, the diffraction efficiency by simulation was 68% and 64% experimentally. The deviation in the diffraction efficiency can be attributed to DOE-fabrication errors.

Fig. 3: Optical reconstruction of the tilted hologram

Using DOE-elements for high power laser radiation needs to be taken care for element damage due to absorption. Absorption measurements have been carried out using caloric method: We exposed the DOE with a CO_2 laser and determine the increase of temperature of the DOE [7].
Table 1 shows that the absorption values for s- and p-polarized waves; they are not influenced by the surface relief structure of the DOE, where a typical structure size is in the range of 50-100μm (it is compared to the absorption value of the flat surface mirror). As it would be expected according to the Fresnel formula the absorption for p-polarisation decreases for smaller incident angle θ.

	θ	DOE	flat mirror
s-polarized	45°	1.48%	1.50%
p-polarized	45°	3.41%	3.15%
p-polarized	25°	2.07%	
p-polarized	8°	1.86%	

Table 1: *Measured absorption values for the DOE (sputtered with gold) and a gold coated flat mirror*

5 Conclusions

We described the realization of diffractive optical elements (DOEs) for CO_2-laser material processing with high power laser radiation. To avoid damage the DOEs are designed as reflective type Kinoforms. The DOE phase transmittance were calculated using an iterative Fourier transform algorithm (IFTA), which allows a flexible element design. During the calculation we consider the 45° inclined illumination. Reflective DOEs were recorded in Silicon by a lithographic method. Silicon is light weight (important for moving optical systems), has a moderate heat conductivity and is easy to be processed. In the case of a pointsymmetrical intensity distribution (-1st and +1st order are used in the reconstruction) the measured diffraction efficiency of the binary Kinoform was 64% (simulation: 68%). The absorption of the DOE for s-polarized light amounts to 1.5% and for p-polarized light to 3.4%.

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