Diffractive elements for annular laser beam transformation

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A diffractive optical system for the transformation of an annular laser beam to a uniform circular beam is presented. It is composed of two diffractive elements which are recorded as surface relief transmission gratings with multilevel discrete binary steps. Our experiments with CO_2 laser radiation show that high diffraction efficiencies and good uniformity of the output beam can be achieved.

The output intensity distribution from high power lasers is generally annular, where it is difficult to control the mode. Consequently, it is desirable to transform the annular beam into a uniformly distributed circular beam. Such a transformation was implemented optically, by exploiting reflective[1] and refractive[2] optical components. Unfortunately, these implementations require highly accurate aspheric optical surfaces, sometimes having extremely small radii of curvature that are relatively difficult to fabricate.

In this letter, we present an approach in which these aspheric surfaces are replaced by diffractive optical elements (DOEs). These elements are realized by exploiting multilevel lithography with computer generated masks[3] so that highly accurate aspheric wavefronts can be obtained relatively easy. To illustrate the validity of this approach, a specific element that transforms an annular laser beam from a CO_2 laser into a circular uniform one is realized and tested.

The optical arrangement, consisting of two DOEs, is schematically illustrated in Fig. 1. The first DOE converts an incident annular beam with uniform intensity and phase into a circular beam with uniform intensity at the position of the second DOE; this conversion is achieved with a coordinate transformation[4] (CT). The second DOE serves as a phase corrector to produce a uniform output phase.

To find the proper CT that the first DOE has to perform, we restrict ourselves to cylindrical symmetry. In this case, the CT may be defined by the one-dimensional transformation

$$r \rightarrow \rho(r), \tag{1}$$

where r and ρ are the radial coordinates in the planes of the first and second DOE, respectively. The coordinate $\rho(r)$ is determined by the energy conservation requirement in cylindrical coordinates, as

$$c_1 \int_{r_{\min}}^{r} r\, dr = c_2 \int_0^{\rho} \rho\, d\rho, \tag{2}$$

where $r_{\min}$ is the inner radius of the annular beam, and c_1 and c_2 are constants. Integrating Eq. (2) on both sides and assuming a unit intensity incoming beam, i.e., $c_1 = 1$, yields

$$\rho(r) = \frac{\sqrt{r^2 - r_{\min}^2}}{c}, \tag{3}$$

where $c^2 = (r_{\max}^2 - r_{\min}^2)/\rho_{\max}^2$, $r_{\max}$ is the outer radius of the annular beam, and $\rho_{\max}$ is the radius of the circular beam. The (normalized) grating vector of a DOE that performs such a CT within the paraxial approximation is[5]

$$K_1(r) = \frac{\rho(r) - r}{z_0}, \tag{4}$$

where z_0 is the distance between the two DOEs. The phase function of this DOE is obtained by integrating the grating vector[5] to yield

$$\phi_1(r) = \frac{2\pi}{\lambda} \int_0^r K_1(r')\, dr' = \frac{\pi}{\lambda z} \left[\frac{r\sqrt{r^2 - r_{\min}^2}}{c} - \frac{r_{\min}^2 \ln(r + \sqrt{r^2 - r_{\min}^2})}{c} - r^2 \right], \tag{5}$$

where the integration constant was chosen as zero.

The phase of the second DOE is also calculated in the grating vector notation. The phase compensation requirement is then expressed as

$$K_2(\rho) = -K_1[r(\rho)], \tag{6}$$

where K_2 is the grating vector of the second DOE. Inserting Eqs. (3) and (4) into Eq. (6), yields

$$K_2(\rho) = \frac{\sqrt{c\rho^2 + r_{\min}^2} - \rho}{z_0}. \tag{7}$$

Finally, integrating this grating vector yields the total phase function of the second DOE as

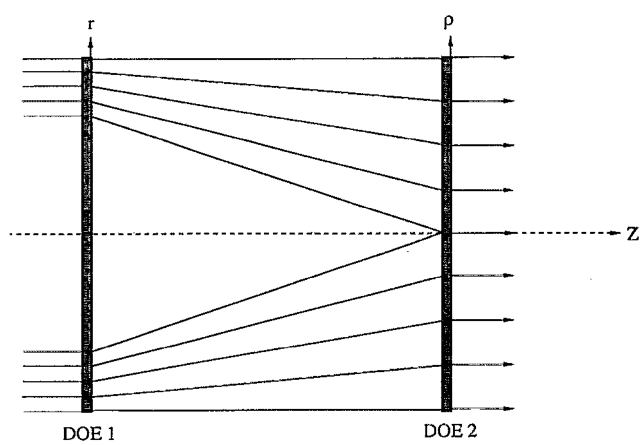

FIG. 1. Optical arrangement consisting of two diffractive optical elements for transforming an annular laser beam into a uniform one.

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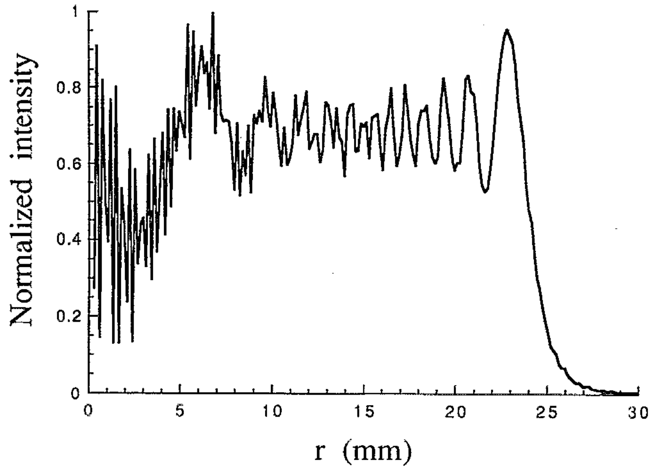

FIG. 2. The calculated intensity distribution at the plane of the second diffractive optical element.

$$\phi_2(\rho)=\frac{\pi}{\lambda z}\{c\rho\sqrt{\rho^2+(r_{\min}/c)^2}+r_{\min})^2 \times \ln[\rho+\sqrt{\rho^2+r_{\min}/c})^2]/c-\rho^2\}. \quad (8)$$

We performed numerical simulations and initial experiments to verify the performance of the first DOE described above. We assumed a DOE with a phase function described by Eq. (5) that is illuminated with a unit amplitude annular beam. For the simulation, we calculated the intensity distribution at the plane of the second DOE by solving numerically the Fresnel diffraction integral,[6] given by

$$I(z,\rho)=\left(\frac{2\pi}{\lambda z}\right)^2\left|\int_{r_{\min}}^{r_{\max}}\exp\{i2\pi[r^2/2\lambda z-\phi_1(r)]\} \times J_0(2\pi\rho r/\lambda z)r\,dr\right|^2, \quad (9)$$

where J_0 is the zero-order Bessel function. The simulation results for a DOE with the parameters $\lambda=10.6\ \mu\text{m}$, $r_{\min}=10$ mm, $r_{\max}=15$ mm, $\rho_{\max}=25$ mm, and $z=200$ mm are presented in Fig. 2. As evident, the calculated intensity distribution is approximately uniform within a cylinder, except for some fluctuations; a high, but very narrow peak on the optical axis ($\rho=0$) was omitted from the figure for clarity. The fluctuations may be attributed to diffraction from the edges of the ring ("Fresnel rings") that are not taken into account in the out ray optics model, and the central peak ("Fresnel point") contains very little energy (less than 1% of the incoming energy) due to its small size.

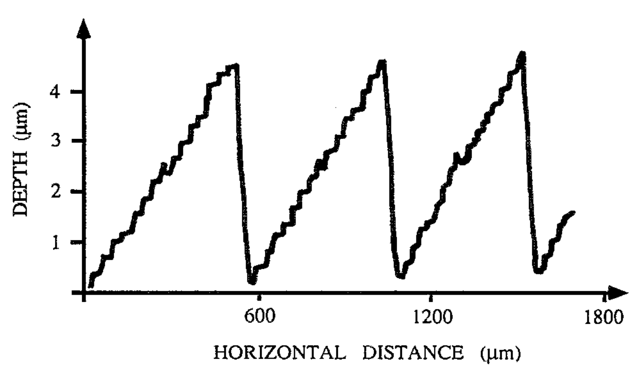

FIG. 3. A surface profilometer trace for a typical section of the diffractive optical element.

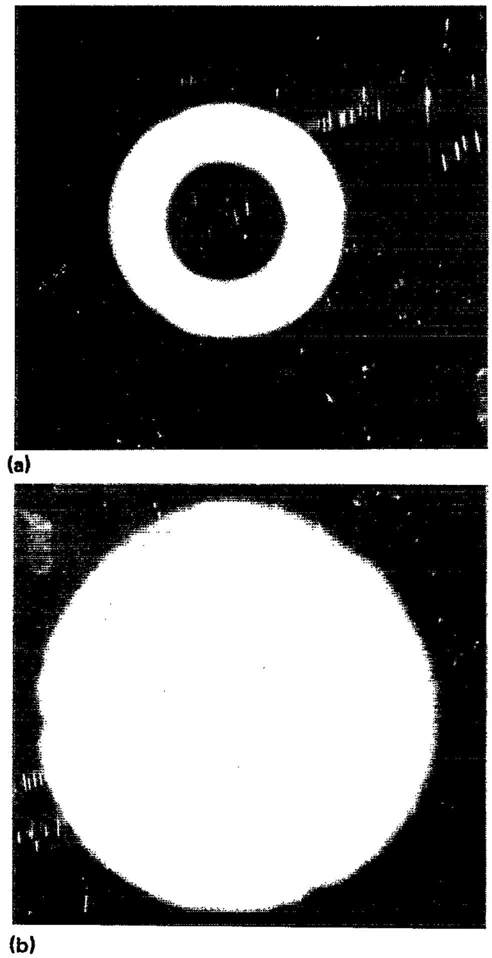

FIG. 4. Liquid crystal thermographic recording of the experimental light intensities: (a) input; (b) output.

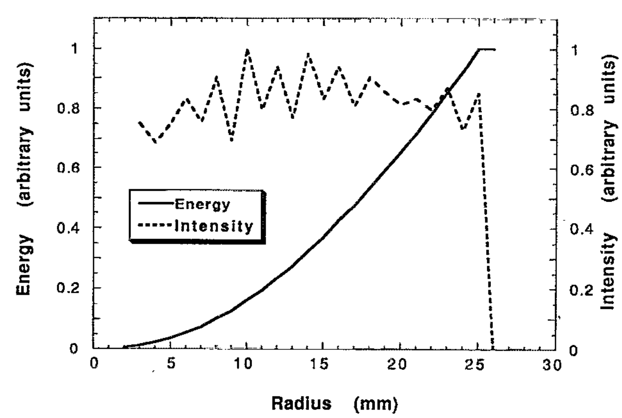

FIG. 5. Relative power $E(r)$ contained within a circle of radius r (solid curve) and the corresponding intensity distribution $I(r)$ (dashed curve) measured at the output plane.

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For the experiment, a DOE, having the same parameters as in the simulation, was recorded as a transmission surface relief grating with 16 discrete binary steps by a multilevel lithography process with four binary masks.[3] Each mask was first plotted by a laser plotter, then demagnified optically and recorded as chrome master mask.[3] The information from each mask was then etched into a single-crystal GaAs wafer with a refractive index of $n=3.27$. A mask aligner with a resolution of approximately 1 μm was used to align each mask onto the GaAs wafer. The etch depth of the mth mask was $2^{-m}\lambda/(n-1)$ so as to provide high diffraction efficiency; with four masks, the theoretical efficiency should be 98.7%.[3] Figure 3 depicts a surface profilometer trace for a typical section of the DOE.

The DOE was then illuminated by a uniform plane wave emerging from a CO_2 laser, magnified by a telescope, and blocked to an annular shape by a ring aperture of gold deposited on a GaAs window. For a qualitative assessment of the optical performance of the DOE, the light intensity distributions at the input and output were detected with a liquid-crystal thermographic recording. The results are shown in Fig. 4. Figure 4(a) shows the light intensity distribution at the input, whereas Fig. 4(b) shows the light intensity distribution at the output. As can be seen, the shapes of the intensity distributions are indeed as expected.

For a more quantitative assessment, the light intensity at the output was measured using a variation of the knife-edge method. The results are shown in Fig. 5. A circular aperture was located at the output and all the radiation passing through it was collected by a detector. The relative power as a function of the radius of the aperture $E(r)$ is depicted by the solid curve. The intensity distribution $I(r)$, given by the dashed curve, was found by dividing the derivative of the relative power by the radius, i.e., $I(r)=[dE(r)/dr]/r$. Due to technical reasons, these measurements were not performed for radiuses below 3 mm. The results indicate that the output intensity is indeed uniform up to approximately 20% accuracy.

The measured diffraction efficiency was approximately 90%, not taking into account losses due to Fresnel's reflections. These may be eliminated by applying AR coating on both sides of the GaAs wafer.[3] We attribute the loss of efficiency compared to the theoretical value to improper etch depths and misalignment errors.

To conclude, we have demonstrated that diffractive elements can perform an annular to circular beam transformation with good accuracy and high efficiency. Further improvement in the accuracy of the transformation should be possible by exploiting iterative technique in the design of the phase functions.[7]

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