Focusing through an interface: scanning and localizing the intensity

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Focusing light through an interface leads to an aberrated intensity distribution that is highly extended with a relatively low peak intensity. We present a method, using a well-chosen annular aperture, that can greatly improve the localization of the intensity about a prescribed point on the axis. Also, the intensity at that point can be increased significantly. By continuously varying the annulus radii, we can scan the intensity peak through the second medium. This localization and scanning method has possible applications in three-dimensional imaging and lithography. © 1998 Optical Society of America

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The present authors and others have recently shown that focusing through a dielectric interface produces strongly aberrated wave fronts.[1-4] An example of this process is shown in Fig. 1. Compared with the case when the two refractive indices are equal, here the axial intensity distribution is elongated and exhibits many secondary peaks.

Although the form of the intensity distribution can be calculated accurately with the results of the studies mentioned above, it is highly desirable to have a means to compensate for the aberrations to decrease the width of the distribution and also to increase the intensity locally. Methods suggested thus far, such as phase masks and adaptive-optics solutions, are difficult to implement in practical optical systems. Although it is relatively easy to realize an annular aperture to reduce on-axis aberrations, this method appears to lower the intensity because only a limited fraction of the incident beam passes the aperture. It is our purpose in this Letter to demonstrate that the use of a well-chosen annular aperture can lead to a simultaneous increase in the intensity and substantial decrease in the width of the axial intensity distribution. In particular, the peak intensity can be increased in this manner. In addition, we present a new scanning mechanism.

In Ref. 2 it was derived that, for the case of an unobscured lens, the electric-field distribution on the z axis (the axis of rotational symmetry, perpendicular to the interface) in the second medium is given by

$$E_x(z) = C(z) \int_0^{\Omega_1} \exp(ik_2 s - ik_1 t) g(\theta_1, z) d\theta_1, \quad (1)$$

with

$$C(z) = \frac{f}{2}(f - d)^2 \left(\frac{z}{f - d} - 1\right) \exp(ik_1 f), \quad (2)$$

$$g(\theta_1, z) = \left(\frac{1}{s^3} - \frac{ik_2}{s^2}\right)(\eta_s + \eta_p \cos \theta_2)\tan \theta_1. \quad (3)$$

The subscript x in Eq. (1) indicates that the incident plane wave is linearly polarized along the x direction. Ω_1 is the semiaperture angle of the lens, f is the focal length, and θ_2 follows from θ_1 through Snell's law. Also, $f - d$ is the distance between the focus of the lens and the interface, k_i ($i = 1, 2$) is the wave number in medium i, and η_s and η_p are Fresnel transmission coefficients. The origin of the z axis coincides with the focal point, and the direction of increasing z is toward the lens. The functions s and t are defined as

$$t(\theta_1) = \frac{f - d}{\cos \theta_1}, \quad (4)$$

$$s(\theta_1, z) = [t^2 + z^2 - 2z(f - d)]^{1/2}. \quad (5)$$

A stationary phase analysis of this integral shows that the main contribution to the intensity at the axial
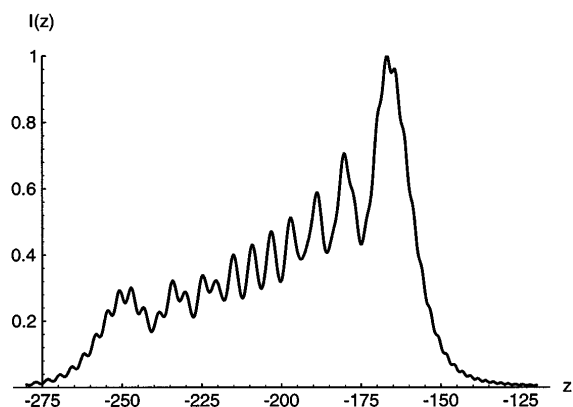

Fig. 1. Intensity distribution (in arbitrary units) along the z axis (in micrometers) for an unobscured lens with a semiaperture angle $\Omega_1 = 45°$ and a focal length of 10^{-2} m. The lens is positioned in air ($n_1 = 1$). The interface with the second medium ($n_2 = 1.51$) is located 300 μm in front of the focus of the lens. The wavelength in air is $\lambda_0 = 632.8$ nm.
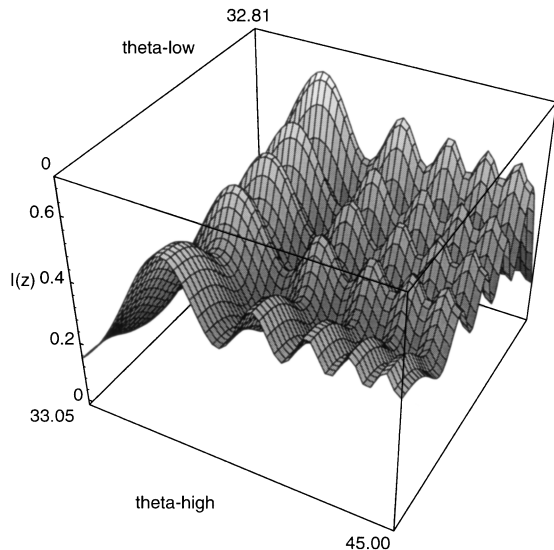
Fig. 2. Intensity $I(z = -203 \ \mu\text{m})$ as a function of θ_{low} and θ_{high}. All other parameters are as in Fig. 1.

position z is due to those rays for which the phase factor is an extremum. It is possible to show that this condition occurs precisely for that ray that is refracted according to Snell's law such that it crosses the axis at z. The angle of incidence in the first medium of this ray is denoted $\theta_{\text{stat}}(z)$. By choosing, instead of an unobscured lens, an annular aperture that corresponds to the angular interval $[\theta_{\text{low}}(z), \theta_{\text{high}}(z)]$ that contains $\theta_{\text{stat}}(z)$, we can modify the axial intensity distribution significantly. By numerically optimizing the size of this angular interval, we can achieve both of our aims (viz., the localization of the intensity around z and the increased intensity at z). Note that this can be done only for points that lie between the so-called geometrical shadow boundaries.[2] As an illustration of our method we show how, e.g., the secondary peak at $z = -203 \ \mu\text{m}$ in Fig. 1 can be selected as the center of the improved intensity distribution. The dependence of the intensity at this particular point on the interval $[\theta_{\text{low}}, \theta_{\text{high}}]$ is depicted in Fig. 2. The optimal annulus (i.e., the one that give the highest intensity) in this case was found to be $[28.04°, 36.71°]$. Note that this interval indeed includes $\theta_{\text{stat}}(z = -203) = 32.7°$. For a lens that obeys the sine condition,[5] the relation between the radius ρ of the annulus (placed in the back focal plane or the exit pupil) and θ is given by $\rho = f \sin \theta$.

The axial intensity distribution for the optimized annulus is shown in Fig. 3. The intensity is now much more localized, and the number of secondary maxima and their heights are both strongly reduced. The intensity profile is indeed centered about the prescribed axial position. Also, the intensity at $z = -203 \ \mu\text{m}$ has changed from 0.47 to 0.70, an increase of more than 48%.

In the same way, the highest peak (at $z = -166.7 \ \mu\text{m}$) in Fig. 1 can be enhanced. For a θ_1 interval of $[0°, 25.51°]$ the intensity at that point is increased by 25%. At the same time, a much narrower intensity profile is obtained. It is striking that we

obtain this increased peak intensity by blocking 63% of the total incident power.

In Fig. 4 the value of θ_{stat} as a function of the axial position is shown. Also, the optimized values (i.e., those that lead to the highest intensity) of θ_{low} and θ_{high} for all axial points z between the geometrical shadow boundaries are depicted. Note that θ_{low} suddenly becomes nonzero near the position of the original maximum. This result is related to the fact that the paraxial rays, which together make up the maximum peak for the case of an unobscured lens, gradually get out of phase with the rays near θ_{stat} as z becomes more negative. Therefore, from a certain z value onward, these paraxial rays are no longer part of the optimized annulus. Also, it is seen that from certain z values on, $\theta_{\text{high}} = 45°$. This is so because θ_{high} cannot exceed Ω_1.

When the annular illumination interval is chosen as $[\theta_{\text{low}}(z), \theta_{\text{high}}(z)]$ the intensity distribution will be centered about z. Not only θ_{stat} but also θ_{low} and θ_{high} are monotonic functions of z. Therefore we can, by varying the radii of the annulus in a continuous manner, scan a single intensity peak through the second medium between the geometrical shadow boundaries. This new scanning mechanism may be useful in, e.g., three-dimensional imaging and lithography.
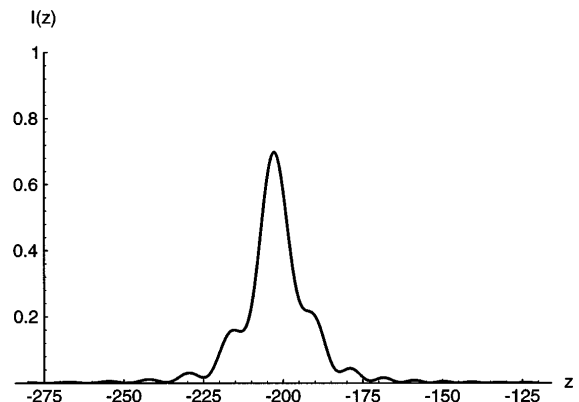

Fig. 3. Intensity distribution along the z axis (in micrometers) for an optimized annular aperture with $28.04° < \theta_1 < 36.71°$. All other parameters and the normalization are as in Fig. 1.
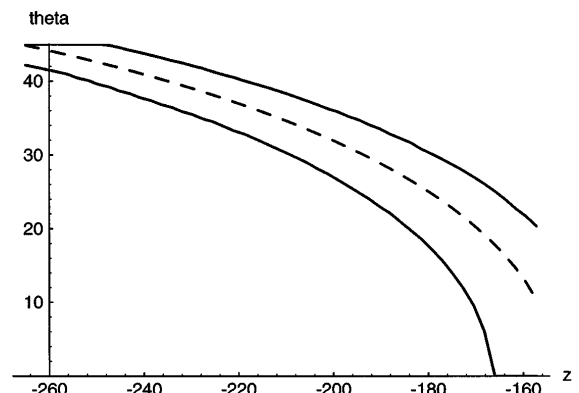

Fig. 4. Stationary phase θ_{stat} (dashed curve) and the two interval limits θ_{low} (lower curve) and θ_{high} (upper curve) that give optimal intensity as a function of axial position z (in micrometers). All parameters are as in Fig. 1.

In conclusion, we have presented a method to improve the width of the axial intensity distribution that results when light is focused through an interface. This method, which can be implemented easily, employs an annular aperture with optimized radii. It results in a higher localized intensity at a prescribed point while reducing the secondary maxima strongly. The intensity of the original peak can also be increased in this manner. In addition, this method provides a novel scanning mechanism.

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