Focal-point shaping of microlenses by amplitude or phase masks

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Abstract: *We present results of numerical investigations into the possibility to shape the focal field distribution by means of amplitude or phase masks on top of a microlens that works in the transition regime between a diffractive and a refractive element. For different applications, such as photolithography or optical tweezers, a specialized intensity distribution in the focal region is desirable. For the trapping of small dielectric particle e.g. a large gradient in the field distribution becomes favourable to compensate for the scattering force, which pushes the particle towards the optical axis. We apply scalar as well as rigorous diffraction theory to calculate the interaction of light with the microlens and analyse the influence of different types of masks (ring-aperture, central stop). As one application we analyse in the depth optical tweezers and calculate the forces in a two-dimensional geometry on particles with different sizes. The field in the focal region of a lens with an aperture suffers from a squeezing in lateral as well as transversal direction causing higher gradients of the field, which allows to trap relative large particles.*

1. Introduction

Microlenses are mostly fabricated by lithographic means and they found applications in the past in illumination systems or for the beam shaping of laserdiodes [1]. In the present work we have investigated some ideas for further applications of microlenses that could be done by employing an additional central or ring aperture onto the lens that can be a phase or an amplitude structure. The impact of these structures for larger lenses is well understood, but the exploitation of applications in conjunction with microlenses is so far not done. The additional structure causes a transformation of the classical well-known intensity pattern in the transmission region into more complex ones, possessing for an appropriate choice of parameters properties such as higher intensity gradients, a tailoring of the field distribution in focal point or the appearance of spots with a high axial-symmetry.

2. Design procedure

The geometry of the problem under consideration is shown in the upper part of Fig. 1. A microlens attached to the surface of a substrate (n=1.5) is illuminated with a plane wave (λ=0.810 nm, TE). The lens is assumed to be cylindrical in the case of a 2D geometry, as in Fig.1. The lens has a diameter of 27 µm and a design focal length of 75 µm. The white line indicates the surface of the lens. On top of the lens is an additional central aperture stop (d=14 µm), which is in the shown figure an amplitude structure. In the case of a phase aperture a supplementary dielectric domain with a spatial extension of one wavelength was added to the surface of the microlens.

The figure shows the intensity distribution computed with a FDTD algorithm [2]. The interaction problem was calculated with this technique in the region of an inhomogeneous dielectric constant and subsequently free space propagation algorithms have been used to calculate the field distribution in the focal region as shown in the lower part of Fig. 1. Algorithms based on the angular spectrum (AS) as well as based on the Rayleigh-Sommerfeld (RS) integral were applied.

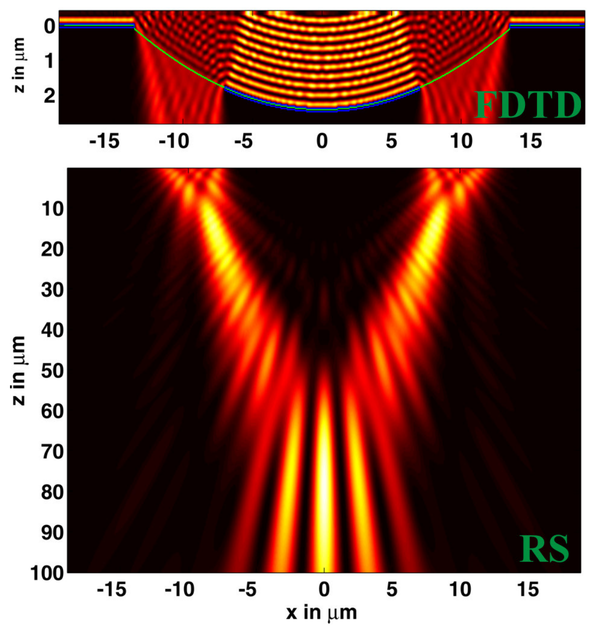

Fig. 1. Intensity distribution behind a lens with aperture

By comparing the rigorously calculated intensity distributions from FDTD data (for the interaction of the light with the lens) with those obtained from a thin-element approach, it can be seen that the field distributions coincide to a good approximation and the application of this approximation theory is justified for lenses in this size-domain.The first observation from the simulations is a shift of the focal point compared to the design focal length, which is a known effect [3].

The second effect is the appearing of more pronounced side lobes in the focal region, which is a well-known phenomenon as the structure behaves essentially like a Toraldo-Filter. The additional rings in the amplitude- or phase-transmission function will cause a tailoring of the transmitted field that can be regarded as a superposition of Bessel-beams for a 3D lens. This allows a smaller spot size, with the disadvantage of stronger side lobes.

3. Optical tweezers

Another kind of beams that can be regarded as a superposition of Bessel-beams, is the bottle beam [4]. Such a beam has an intensity close to zero at a point on the optical axis surrounded in all spatial directions with a regions of high intensity. By optimizing the aperture radius such that the field intensity coincides with the demands for a bottle beam, a lens could be designed in both dimensions that generate a bottle beam.

The left side of Fig. 2 shows the amplitude distribution generated by a 2D lens with the same geometrical parameters as in Fig. 1 but the outer diameter of the central aperture stop is now d_O=18 µm and the inner diameter is d_I=7 µm. The optimum geometry for the generation of a bottle beam in 3D would be an inner diameter of d_I=16 µm and an outer diameter of d_O=21 µm.

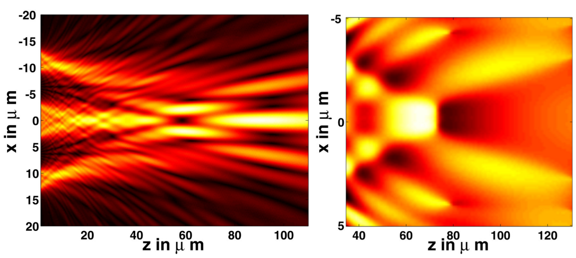

Fig. 2. Amplitude behind a lens with ring aperture (left) and longitudinal gradient force (right) acting on a small dielectric particle

Such a beam can be applied for an optical tweezer, which is a highly focused laser beam that traps particles stable. This is possible at points where all the forces exerted by the wavefield are zero. For particles much smaller than the wavelength the force can be decomposed into a gradient force that is proportional to the gradient of the intensity and the polarizability, and a scattering force, proportional to the square of the polarizability. For particles with an index contrast lower than unity, the force will drag the particles toward points with a low intensity. A central portion of the longitudinal component of the gradient force for the proposed bottle beam in a 2D geometry is shown in the right side of Fig. 2. In the figure black denotes a negative force and white a positive respectively. Along the optical axis close to the geometrical focus the beam has its intensity zero and the longitudinal force suffers from a change of sign, attracting the particle towards this point. It can be stably trapped at this point as long as the scattering force remains small.

Contrary, particles with an index contrast larger than unity can be trapped at points with a large gradient in the intensity. By using apertures, the gradient of the intensity can be controlled. Points with the highest gradient do not appear in the focal-plane but further maxims along the optical axis before the focus suffers from a significant enhancement in intensity. The enhancement is restricted to a small spatial extension leading to strong gradients in the intensity. Figure 3 a) shows the intensity along the optical axis for a 3D lens with f=92 µm, a diameter of d=27 µm. The outer diameter of the amplitude ring was d_O=23 µmm and the inner diameter was d_I=10 µm.

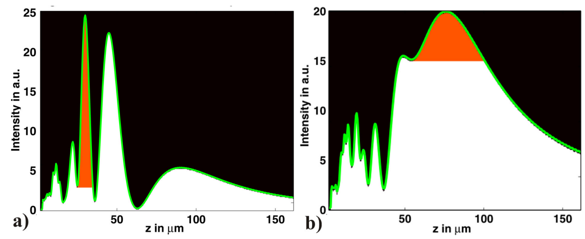

Fig. 3. Intensity along the optical axis behind a lens with a ring aperture

4. Confocal microscopy

Another potential application of the partially obstructed microlenses can be confocal microscopy for optical inspection tools. The intensity peak needs to be very symmetric about the maximum in the direction of light propagation. The unobstructed microlens (f=92 µm, d=27 µm) yields an intensity peak at about 90µm in front of the lens. The peak is unsymmetrical and hence not optimal for confocal microscopy. Applying an obstructing ring (d_O = 18.2 µm, d_I = 6.8 µm) onto the surface of the curved side of the microlens, the profile becomes much more suitable for the application(Fig. 3 b).

5. Conclusions

The integration of central- or ring-apertures onto a microlens allows the creation of intensity patterns with interesting characteristics. The use of a simple central aperture leads foremost to a reduction of the spot size. Field distributions generated with ring-apertures have been investigated for an application to optical tweezers. It is possible to create optical bottle beams, which are favorable for the trapping of particles with an index contrast lower than unity. It was shown that field distributions with high gradients can be generated, such that particles with an index contrast larger than unity can be trapped in the optical tweezer. Further on symmetric intensity distributions favorable for optical inspection tools can be generated along the axis.

6. Acknowledgement

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