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Enhanced two-point resolution using optical eigenmode optimized pupil functions

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Abstract
Pupil filters have the capability to arbitrarily narrow the central lobe of a focal spot. We decompose the focal field of a confocal-like imaging system into optical eigenmodes to determine optimized pupil functions, that deliver superresolving scanning spots. As a consequence of this process, intensity is redistributed from the central lobe into side lobes restricting the field of view (FOV). The optical eigenmode method offers a powerful way to determine optimized pupil functions. We carry out a comprehensive study to investigate the relationship between the size of the central lobe, its intensity, and the FOV with the use of a dual display spatial light modulator. The experiments show good agreement with theoretical predictions and numerical simulations. Utilizing an optimized sub-diffraction focal spot for confocal-like scanning imaging, we experimentally demonstrate an improvement of the two-point resolution of the imaging system.

Keywords: pupil filter, spatial light modulator, imaging, optimization

1. Introduction

Using pupil filters, the lateral diffraction limited point spread function (PSF) or focal spot of an imaging or focusing system can be altered such that the width of the central lobe is reduced while the intensity is redistributed into the sidelobes [1–4]. Indeed, given a suitable pupil modification, the central lobe could in principle be made arbitrarily narrow and the sidelobes can be pushed arbitrarily far away from the center. Possible applications for this effect include e.g. superresolved imaging [5] or increased optical data storage [6]. Some superresolving pupil filters have been demonstrated to work experimentally [7–9]. However, squeezing the central lobe by a few tens of per cent beyond the diffraction limit induces its intensity to drop by orders of magnitude, while the intensity of the sidelobes rises correspondingly. Thus the practical implementation of this method remains difficult, as it requires very accurate light shaping to achieve high resolution gains [10].

Here, we investigate the use of a liquid crystal spatial light modulator (SLM) as dynamic pupil filter in a systematic manner for this purpose. The optical eigenmode (OEi) method [11] is used to calculate pupil functions that are optimized for different intensities of the central lobe and variable sizes of the field of view (FOV). These functions are then encoded onto a dual display SLM system and the agreement between the theoretical and experimental focal spots is analyzed. We determine intensities and sizes of the central lobe and the FOV that can be experimentally realized.

To show a possible application of the OEi pupil filters, we have experimentally implemented a filter in the context of a simple imaging setup. As the width of the central lobe is reduced in the lateral direction, a suitable spot is used for confocal-like scanning of in-focus pairs of holes, demonstrating enhanced two-point resolution compared to the unobstructed pupil.

The paper is organized as follows: in section 2, we briefly review the OEi optimization method. Section 3 depicts the
experimental setup used. The confocal-like scanning process and its numerical simulation is described in section 4. In section 5, we present a comprehensive study of simulated and experimentally acquired focal spots to determine the practical beam shaping limit of the configuration and its confocal imaging capabilities. The applicability of the filters for a broader range of imaging applications is discussed in section 6. The paper finishes with conclusions in section 7.

2. Focal spot optimization using optical eigenmodes

In order to calculate the pupil functions to be displayed on the SLM system, we employ the OEi method [11, 12] squeezing laterally the central lobe of the focal spot. For a given set of input fields and parameters, this enables us to find in a single iteration the pupil modification which delivers the smallest possible focal spot in a region of interest (ROI) while keeping the intensity of the spot maximum. To achieve lateral squeezing, the size of the ROI is usually about the size of the diffraction limited focus. For the studies in this paper we consider only radially dependent scalar fields \( F(r_1) \) in the focal plane where \( r_1 \) is the lateral radius (however, the OEi method is just as capable of treating the electromagnetic field as fully vectorial [11]). Symmetry maintaining scalar propagation implies that the field \( E(r_2) \) does only depend on the lateral radius \( r_2 \) in the pupil plane.

To employ the OEi optimization method, the field \( E(r_2) \) in the pupil plane and the field \( F(r_1) \) in the focal plane of the lens are decomposed into \( N \) fields \( E_i(r_2) \) and \( F_i(r_1) \),

\[
E(r_2) = \sum_{i=1}^{N} a_i E_i(r_2), \quad (1)
\]

\[
F(r_1) = \sum_{i=1}^{N} a_i F_i(r_1), \quad (2)
\]

with complex coefficients \( a_i \). Since the lens is a linear optical system, the complex coefficients \( a_i \) are identical for the fields in both planes. Using the decomposition in (2), the beam width \( w \), expressed as the second order moment of the intensity distribution in the focal plane, can be written as [11]

\[
w = 2 \sqrt{\frac{\mathbf{a}^{\dagger} \mathbf{M}^{(2)} \mathbf{a}}{\mathbf{a}^{\dagger} \mathbf{M}^{(0)} \mathbf{a}}} \quad (3)
\]

with \( \mathbf{a} = (a_1 \cdots a_N)^T \), \( \mathbf{a}^{\dagger} = (a_1^{\dagger} \cdots a_N^{\dagger}) \), and the \( N \times N \) operators \( \mathbf{M}^{(0)} \) and \( \mathbf{M}^{(2)} \) having elements

\[
\mathbf{M}^{(0)}_{ij} = \int_{0}^{R_1} F_i^*(r_1) F_j(r_1) 2\pi r_1 \, dr_1, \quad (4)
\]

\[
\mathbf{M}^{(2)}_{ij} = \int_{0}^{R_1} r_1^2 F_i^*(r_1) F_j(r_1) 2\pi r_1 \, dr_1, \quad (5)
\]

where the integration is carried out over a circular ROI with radius \( R_1 \). From the definitions in (4) and (5) it follows that both \( \mathbf{M}^{(0)} \) and \( \mathbf{M}^{(2)} \) are Hermitian and consequently feature a spectrum of real eigenvalues and orthogonal eigenvectors. Employing \( \mathbf{M}^{(0)} \) and \( \mathbf{M}^{(2)} \), the OEi optimization of the coefficients \( a_i \) is then performed in two stages: firstly, we determine a set of orthonormal optical eigenmodes with respect to the ROI. This step also delivers the maximum total intensity in the ROI. Secondly, using this orthonormal set, the spot size in the ROI is minimized.

2.1. Maximizing the intensity

If \( \mathbf{a} \) in (3) is one of the \( N \) eigenvectors \( \mathbf{v}_i^{(0)} \) of \( \mathbf{M}^{(0)} \), then its corresponding eigenvalue \( \lambda_i^{(0)} \) equals the total intensity in the ROI. Hence \( \mathbf{M}^{(0)} \) is called intensity operator. When the \( \lambda_i^{(0)} \) are ordered by descending magnitude, a field \( F_i(r_1) \) composed according to (2) from the elements of \( \mathbf{v}_i^{(0)} \) features the maximum possible intensity in the ROI for the given set of incident fields \( E_i(r_2) \) and the constraint \( \mathbf{a}^\dagger \mathbf{a} = 1 \). Using \( \mathbf{v}_2^{(0)} \) results in the second highest intensity and so on. To minimize the spot size while keeping the intensity maximal, the red first \( M \) eigenvalues \( \lambda_i^{(0)} > T \lambda_1^{(0)} \) are selected with \( T \in [0, 1] \) representing a relative intensity threshold. Using the elements \( v_{k_i}^{(0)} \) of their corresponding eigenvectors, within the ROI a set of \( M \) orthonormal optical eigenmodes

\[
F_k^{(0)}(r_1) = \frac{1}{\sqrt{\lambda_k^{(0)}}} \sum_{i=1}^{N} v_{k_i}^{(0)} F_i(r_1) \quad (6)
\]

is composed, which we use in section 2.2 to minimize the spot size.

2.2. Minimizing the spot size

To minimize the spot size in the ROI, the set of orthonormal modes \( F_k^{(0)}(r_1) \) from (6) is used in the definitions (4) and (5) of the operators \( \mathbf{M}^{(0)} \) and \( \mathbf{M}^{(2)} \). If now \( \mathbf{a} \) in (3) is any normalized eigenvector \( \mathbf{v}_i^{(2)} \) of \( \mathbf{M}^{(2)} \), then the denominator of the second order moment in (3) is unity (as the modes \( F_k^{(0)}(r_1) \) are orthonormal). In that case the spot size \( w \) defined in (3) is a function of the corresponding eigenvalue \( \lambda_i^{(2)} \). Thus we term \( \mathbf{M}^{(2)} \) the spot size operator. Consequently a superposition of the modes \( F_k^{(0)}(r_1) \) using the elements \( v_{k_i}^{(2)} \) of the eigenvector \( \mathbf{v}_k^{(2)} \) that corresponds to the minimum eigenvalue \( \lambda_k^{(2)} \) exhibits the smallest possible spot in the ROI. In conclusion, and referring to the initial set of fields \( E_i(r_2) \) and \( F_i(r_1) \) in (1) and (2), the field \( F_{\text{min}}(r_1) \) featuring the minimum focal width in the chosen ROI results from the superposition

\[
E_{\text{min}}(r_2) = \sum_{i=1}^{N} \sum_{k=1}^{M} v_{k_i}^{(2)} \sqrt{\frac{\lambda_i^{(0)}}{\lambda_k^{(0)}}} E_i(r_2) \quad (7)
\]

of the fields \( E_i(r_2) \) on the SLM.

3. Experimental setup

The setup used for the experiments is depicted in figure 1. It consists of two parts, one for creating the illumination and one for detection and imaging.

In the illumination part, the beam of a linearly polarized HeNe laser (\( \lambda = 633 \text{ nm} \)) is expanded and is sent to the
Figure 1. Experimental setup to create and analyze optimized spots and to perform scanning imaging using these spots. BE: beam expander; P1, P2: polarizers; ISLM: intensity SLM; PSLM: phase SLM; M: mirror; BS1, BS2: 50/50 beam splitter; I: iris; CCD: CCD camera. The lenses Ln have the following focal lengths \( f_1 = f_2 = 400 \text{ mm}, \ f_3 = f_5 = 1 \text{ m}, \ f_6 = 500 \text{ mm}, \ f_7 = 100 \text{ mm}. \)

first display of an 8 bit Holoeye HEO 1080 P dual display SLM system. This first SLM modulates the intensity of the light (ISLM) and the beam is imaged onto the second display that shapes the phase front (PSLM). The PSLM was used in standard first order configuration [13]. Each display features 1920 pixel \( \times \) 1080 pixel resolution with a pixel pitch of 8 \( \mu \text{m}. \) The intensity modulation works in conjunction with a pair of crossed polarizers P1 and P2. After passing the first polarizer P1, the polarization of the light is rotated depending on the 8 bit value displayed on the ISLM. The second polarizer P2 then actually performs the intensity modulation. A \( \lambda/2 \) plate turns the polarization into the orientation required for phase modulation by the PSLM. The pair of lenses L1 and L2 forms a telescope to image the ISLM onto the PSLM. Finally, lens L3 focuses the complex modulated light in the sample plane. The distances in the setup are chosen such that with respect to the sample plane, which we consider to be in space domain, the SLM displays are situated in the reciprocal domain. This means that the PSLM is positioned in the back focal plane of L3. Reciprocal planes are indicated by dotted lines in figure 1.

The beam path of the detection part is divided by a beam splitter BS1 into two arms, Arm 1 and Arm 2, of which only one is used at a time. In Arm 1, whose beam path is dotted in figure 1, the sample plane is imaged via lens L4 with \( 10 \times \) magnification onto a CCD camera (Basler pilot piA640-210gm, 648 pixel \( \times \) 488 pixel resolution, 7.4 \( \mu \text{m} \) pixel pitch). This enables us to analyze the focal spot with a resolution of 0.74 \( \mu \text{m} \) per camera pixel. Arm 2 is utilized for the scanning imaging. The light transmitted through the sample is collected by lens L5, which has identical NA as L3. An iris I that is positioned in the back focal plane of L5 truncates the beam to a diameter identical to the one incident on the PSLM. This ensures that L3 and L5 also have the same effective NA. The lenses L6 and L7 and their positions are selected such that the sample plane is imaged with \( 3 \times \) magnification onto the camera.

We make some further remarks about the SLM system:

- Of each display’s available 1920 pixel \( \times \) 1080 pixel array, we use the central circular area of 1080 pixel in diameter.
- A calibration was carried out for both displays such that their 8 bit range corresponds to a linear real amplitude range from 0 to 1 and a linear phase range from 0 to \( 2\pi \) respectively.
- Aberrations due to unevenness of the display surfaces were corrected by a wavefront correction method similar to the one described in [14]. This correction method is generally applicable to SLM systems and not specific for the initial pupil decomposition \( E_i(r_p) \).
- The ISLM not only rotates the polarization of the incident light but at the same time induces a phase shift. This phase shift dependency was measured with respect to the displayed 8 bit value and is subtracted from the phase displayed on the PSLM.
- Ideally the lenses L1 and L2 should image a pixel coordinate on the ISLM to the same pixel coordinate on the PSLM. By displaying an alignment cross on both displays we ensure a pixel matching of \( \pm 2 \) pixel. This corresponds to a relative error of \(<0.2\%\) and can be neglected if the displayed mask does not exhibit such fine features.

4. The imaging process and its numerical simulation

In conventional confocal laser scanning microscopy either a focused beam is scanned over the sample using a scanning mirror or the sample is scanned through the beam on a translation stage [15]. The beam/sample interaction is imaged onto a pinhole in front of a detector to cancel out scattering light from outside the focal volume. An image is then composed from the intensities acquired at each scanning coordinate. In the case of the beam scanned over the sample,
the beam needs to be descanned for detection by sending the light back over the same scanning mirror or the pinhole needs to be moved with the beam.

### 4.1. Confocal imaging and resolution limits with our setup

For the setup described in section 3 the SLM fulfills the scanning part and the pinhole is substituted by a 3 pixel × 3 pixel square on the CCD that moves together with the beam. This square is small compared to the diffraction limited focal spot featuring a FWHM of about 30 pixel. The scanning of the beam is realized by adding a linear phase gradient on the PSLM, displacing the beam in the sample and the CCD plane. So the PSLM effectively acts as a scanning mirror. The image is then composed from the intensities, that for each displacement are averaged in the small square.

The theoretical focal width of the scanning beam can be calculated using the effective NA of lens L3. From the SLM specifications given in section 3 it follows that the beam diameter incident on lens L3 equals 8.64 mm. With the focal length \( f_3 = 1 \text{ m} \), lens L3 has an effective NA of \( 4.32 \times 10^{-3} \). Regarding to the Abbe limit of \( 0.5 \lambda / \text{NA} \), the scanning beam thus features a diffraction limited full width at half maximum length of the beam is realized by adding a linear phase gradient on the SLM, displacing the beam in the sample and the CCD plane. So the PSLM effectively acts as a scanning mirror.

### 4.2. Simulation of the imaging process

To simulate the generation of sub-diffractive focal spots and analyze their suitability for confocal-like imaging of in-focus pinholes. Therefore, we consider the imaging of two in-focus pinholes. Thus the intensity distribution \( I \) is then simulated as follows for each scanning position:

\[
\begin{align*}
\text{(i) } A(x, y) &= F(x, y) \cdot \text{SLM} \\
\text{(ii) The detection part of the setup in figure 1 is coherent. Thus the intensity distribution } I_c(x, y) \text{ on the CCD is given by the square of the complex convolution of (8) with the complex field } F_c(x, y) \text{ of the Airy disc}.
\end{align*}
\]

As the APSF we use the complex field of the Airy disc.

### 5. Results

Past studies \cite{1-4} have shown that the spot size, the spot intensity, and the distance to the sidelobes obey the qualitative rules of (1) decreasing the spot size results in a decreased spot intensity and (2) moving the sidelobes further away from the spot decreases the spot intensity. In the following these parameters are investigated first in simulations (section 5.1) and then experimentally (section 5.2) for spots generated with our SLM system. Furthermore, the suitability of the spots for confocal-like imaging of in-focus objects is analyzed in simulations (section 5.1) and verified by experiments (section 5.3). More precisely, to quantify the resolution capabilities of an incoherent imaging system it is sufficient to determine its intensity PSF. However, in the case of a coherent detection process it is necessary to investigate at least two points next to each other to correctly deal with interference \cite{18}. Thus, with respect to the application example in section 5.3, we utilize the two-point resolution criterion to study the lateral resolution.

#### 5.1. Simulations on sub-diffractive focal spots

In this section, we simulate the generation of sub-diffractive focal spots and analyze their suitability for confocal-like imaging of in-focus pinholes. Therefore, we consider shaping the intensity and phase of the field \( E(r_p) \) in the focal plane of lens L3 with a dynamic range of 8 bit and a radial resolution of 540 pixel (which maximizes the used area of the SLM). The SLM is divided into \( N = 540 \) non-overlapping rings of 1 pixel width, each of which represents one of the fields \( E_i(r_p) \) in (1) and accounting for all of the system’s radial degrees of freedom. For each of the rings the resulting field \( F(r_f) \) in the focal plane is calculated using the scalar radial symmetric representation of Huygen’s integral \cite{19}. The simulation was carried out with a pixel pitch of 0.74 \( \mu \text{m} \) and a radial resolution of 244 pixel, which equals half of the CCD sensor’s diameter. This corresponds to projecting the focal plane of lens L3 with 10× magnification onto the CCD camera, as it happens in Arm 1 of the setup in figure 1.

Using the fields \( F(r_f) \), the OEi optimization was carried out with the ROI radius \( R_i \), varying in steps of 0.03 \( w_{\text{Airy}} \), between 0.09 \( w_{\text{Airy}} \) and 2.30 \( w_{\text{Airy}} \), with the width of the Airy disc \( w_{\text{Airy}} = 73.3 \mu\text{m} \). The intensity thresholds were chosen to be \( T = 10^{-p} \) with \( p = 1, 2, \ldots, 6 \). The threshold \( T \) in combination with the ROI radius influences the number \( M \) of OEi that are used to minimize the spot size (see also section 2.1). The optimized fields \( F_{\text{min}}(r_f) \) were azimuthally interpolated to 488 pixel × 488 pixel (corresponding to the CCD’s central area) and the following spot parameters were calculated for each intensity distributions \( |F_{\text{min}}(r_f)|^2 \):

- the width \( w_{\text{spot}} \) of the central spot was quantified as the FWHM,
- the Strehl ratio \( S \), defined as the quotient of the peak intensities of spot and the Airy disc \( w_{\text{Airy}} \),
- the distance \( d_{\text{sl}} \) to the sidelobes was measured between the central spot’s peak and the peak of the nearest side lobe of at least 10% of the spot’s peak intensity,
- the relative spot intensity \( I_{\text{rel}} \) was quantified as the ratio between the peak intensities of the central spot and the intensity of the nearest side lobe as defined in the previous point.

However, even with knowledge of these parameters it is not trivial to decide whether or not a spot is suitable for an imaging application. A small central spot is unusable if its
intensity is too low compared to the surrounding sidelobes and/or these sidelobes are too close to the central spot. To quantify the two-point resolution, we simulated the scan along a 220 μm long line through two transmissive holes using a step width of 1 μm between the scanning positions. The separation between the holes was varied in steps of 1 μm as well. The absolute two-point resolution limit \( R_{abs} \) was then quantified in terms of the Rayleigh criterion as the distance for which the two-point sources were resolved with 26.5% contrast [21].

Figures 2(a)–(d) give an overview of the spot parameters and the achievable resolution. In each of the plots the horizontal and vertical axis depict the spot size \( w_{spot} \) and the distance \( d_{SL} \) to the sidelobes relative to the FWHM \( w_{Airy} = 73.3 \mu m \) of the Airy disc. The color codings in figures 2(a)–(d) show the number \( M \) of OEi used in the optimization (figure 2(a)), the Strehl ratio \( S \) (figure 2(b)), the relative spot intensity \( I_{rel} \) (figure 2(c)), and the relative two-point resolution \( R_{rel} \) (figure 2(d)). The latter is scaled as a ‘resolution gain’ in the way \( R_{rel} = R_{abs,Airy}/R_{abs,spot} \) to the absolute resolution limit \( R_{abs,Airy} \) when scanning with the Airy disc. Thus a value of \( R_{rel} = 2 \) would correspond to twofold increased resolution.

From the simulations we obtained \( R_{abs,Airy} = 83 \mu m \), which is in agreement with the theoretical limit of \( 0.56\lambda/NA = 82.1 \mu m \) given in section 4.1. Furthermore, simulations of the Airy disc and three example spots are illustrated in figures 3(i)–(l) with their corresponding parameters listed as ‘S’ values in table 1.

In figure 2(a) we observe that with an increasing number \( M \) of modes the sidelobes can be pushed further away from a central spot of constant size. At the same time the Strehl ratio \( S \) in figure 2(b) and the relative spot intensity \( I_{rel} \) in figure 2(c) decrease. This is due to the lower intensity of the higher order OEi (see section 2.1). Furthermore \( S \) and \( I_{rel} \) decrease with decreasing spotsize \( w_{spot} \). All these findings agree with the qualitative rules stated at the beginning of section 5. The simulated relative resolution \( R_{rel} \) in figure 2(d) generally decreases with decreasing spot size. But at some point this effect stops due to a parameter combination in which the sidelobes are too close to the spot and/or the relative spot intensity \( I_{rel} \) too low to resolve the two simulated holes with sufficient contrast. This parameter combination is different for different \( M \) numbers and can be gathered from figure 2.

### Table 1. Simulated (S) and experimentally (E) measured spot parameters for the Airy disc and three example spots, which are illustrated in figures 3(m)–(o) (simulation) and figures 3(r)–(t) (experiment).

<table>
<thead>
<tr>
<th>Param.</th>
<th>Airy</th>
<th>Spot 1</th>
<th>Spot 2</th>
<th>Spot 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M )</td>
<td>—</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( w_{spot}/w_{Airy} )</td>
<td>S</td>
<td>1 0.61</td>
<td>0.71</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>1 0.61</td>
<td>0.74</td>
<td>—</td>
</tr>
<tr>
<td>( d_{SL}/w_{Airy} )</td>
<td>S</td>
<td>— 1.21</td>
<td>1.84</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>— 1.25</td>
<td>1.85</td>
<td>—</td>
</tr>
<tr>
<td>( S )</td>
<td>S</td>
<td>— 0.022</td>
<td>0.0038</td>
<td>— 0.7</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>1 0.021</td>
<td>0.0037</td>
<td>— 0.88</td>
</tr>
<tr>
<td>( I_{rel} )</td>
<td>S</td>
<td>— 1.2</td>
<td>0.88</td>
<td>0.0083</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>— 1.3</td>
<td>0.91</td>
<td>—</td>
</tr>
<tr>
<td>( R_{abs}/1 \mu m )</td>
<td>S</td>
<td>83</td>
<td>65</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>61</td>
<td>68</td>
<td>61</td>
</tr>
<tr>
<td>( R_{rel} )</td>
<td>S</td>
<td>1 1.28</td>
<td>1.22</td>
<td>1.36</td>
</tr>
</tbody>
</table>

### 5.2. Experimental spot characterization

In this section, we explore to what extent the simulated spots can be produced experimentally. The optimized fields
Figure 3. (a)–(d) Real amplitude and (e)–(h) phase of fields $E(r_p)$ in the SLM plane, that correspond to ((a), (e)) the Airy disc and ((b), (d), (f)–(h)) three example spots: ((b), (e)) Spot 1, ((c), (g)) Spot 2, and ((d), (h)) Spot 3. (i)–(l) Simulated and (m)–(p) experimentally resulting normalized intensity distributions $|F(r_f)|^2$ in the focal plane: ((i), (m)) Airy disc, ((j), (n)) Spot 1, ((k), (o)) Spot 2, and ((l), (p)) Spot 3. The parameters of the focal spots are listed in table 1. The interference fringes visible in (m)–(p) are due to multiple reflections of the coherent laser light within the CCD sensor window.

$E_{\text{min}}(r_p)$ obtained in section 5.1 are azimuthally interpolated to 1080 pixel $\times$ 1080 pixel (examples are shown in figures 3(a)–(h)) and encoded on the SLM system. For each of them the resulting intensity distribution $|F_{\text{min}}(r_f)|^2$ is recorded with 10× magnification on the CCD using Arm 1 of the setup in figure 1. Then the parameters $w_{\text{spot}}$, $S$, $d_{\text{SL}}$, and $I_{\text{rel}}$ are measured as specified in section 5.1.

The results are presented in figures 4(a)–(c), which correspond to the simulated results in figures 2(a)–(c) (note that compared to figures 2(a)–(c), figures 4(a)–(c) have a smaller range of the horizontal axes, but the same scaling relationship). In addition, the experimentally acquired intensity distributions of the Airy disc and three example spots are illustrated in figures 3(m)–(p) with the measured parameters listed as ‘E’ values in table 1.

Comparing the simulated results in figures 2(a)–(c) and the experimental ones in figures 4(a)–(c), we observe good agreement for Strehl ratios $S > 0.003$ and relative spot intensities $I_{\text{rel}} > 0.7$. The more the spot intensity drops below these values, the bigger the mismatch between simulation and experiment. Consequently the spots in figures 3(n) and (o) with $S = 0.021$ and 0.0037 also visually agree with their simulated counterparts in figures 3(j) and (k). On the contrary in figure 3(p), which should show a spot with simulated Strehl ratio $S = 1.7 \times 10^{-5}$, no well defined central peak exists. This lack of agreement between simulations and experiment for low spot intensities is not due to the pixelation and limited dynamic range of the SLM system, as the simulations have been carried out with the actual SLM’s bit depth and resolution. Such limitations may arise due to residual phase and amplitude noise induced by the SLM system. The beam shaping process itself might not be accurate enough e.g. due to pixel noise or the calibrations not leading to the required precision. Furthermore, there might be residual aberrations which cannot be entirely

J. Opt., 13 (2011) 105707
S Kosmeier et al
canceled out by the wavefront correction. Thus in future, results could be improved using more accurate beam shaping devices as well as more advanced calibration and aberration correction methods.

### 5.3. Imaging with optimized focal spots

In this section, we experimentally analyze the suitability of complex optimized focal spots for confocal-like imaging of a thin in-focus object and compare the results to the simulations. A test target featuring pairs of 10 μm diameter transmissive holes on black film with hole separations \( d_{\text{holes}} \) varying in steps of 1 μm was scanned as described in section 4.1 with the Airy disc and an optimized focal spot. For the latter, we have chosen Spot 1 (see figure 3 and table 1), which should give a good resolution gain and whose experimentally measured parameters did not show any noticeable disagreement with the simulations. The scanning was performed over a 220 μm × 110 μm sized area at 64 × 32 uniformly spaced points for hole separations of \( d_{\text{holes}} = 83 \) and 65 μm. These separations correspond to the simulated two-point resolution limits of the Airy disc and Spot 1, as noted in table 1.

The top row of pictures in figure 5(a) shows the pairs of transmissive holes imaged with a widefield microscope (Nikon ECLIPSE Ti-S, Objective: Nikon Plan Fluor, 40 × /0.75). Furthermore, figure 5(a) illustrates for each of the hole pairs the simulated and experimentally obtained intensity distributions resulting from scans with the Airy disc and Spot 1. Figures 5(b)–(e) depict profiles along a horizontal line through the simulated (figures 5(b) and (c)) and experimentally acquired intensity images (figures 5(d) and (e)). For each of the utilized scanning spots the key in figures 5(b)–(e) features the contrast \( C \) measured between the smaller of the two main maxima and the central minimum.

The simulated and experimentally acquired intensity distributions and profiles look similar and the contrast values of simulation and experiment are in reasonable agreement. The results in figures 5(d) and (e) show that within a few per cent of uncertainty the Rayleigh resolution criterion is experimentally fulfilled for \( d_{\text{holes}} = 83 \) μm by the Airy disc and \( d_{\text{holes}} = 65 \) μm when scanning with Spot 1. This is in agreement with the simulated values in table 1.

### 6. Discussion

The optimization we carried out was aiming to reduce the focal width in the lateral direction similarly to past research [1–4]. Usually a decrease of the spot size in the lateral direction results in an axial elongation and vice versa [22, 23] and in [11] it has been shown that this is also the case for the OEi optimization. Thus the focal spots presented in this paper are well suitable to confocally image a thin in-focus sample. Extending the approach to high NA optics [12] would enable the imaging of thin stained tissue slices, for example. However, applied to a 3D sample, the axial resolution would seriously suffer, losing the sectioning capabilities of confocal microscopes. It has been shown theoretically [24] and experimentally [25], that pupil filters can also axially squeeze the focal spot. As the designs in [24, 25] were unoptimized binary filters with three zones, it would be interesting to apply the OEi optimization method [11] for axial optimization with more degrees of freedom in the future and to practically explore the 3D focusing limits stated in [22].

Extending the imaging to high NA optics, an application to fluorescence imaging would be interesting. Simulations (results not shown in this paper), in which the detection process was assumed to be incoherent, proposed lateral two-point resolution gains between 1.4 and 1.6 with the experimentally producible spots. However, potential photobleaching of the sample caused by the sidelobes and the reduced Strehl ratio of the optimized spots would require further investigations for any practical implementation. Higher resolution gains could also be achieved through multiphoton processes.

In general the OEi method in combination with an SLM system as dynamic pupil filter could add great flexibility to confocal setups in terms of tailoring the focal spot for certain measurement tasks.

### 7. Conclusion

We systematically investigated the practical usage of a dual display state-of-the-art SLM system utilized as a pupil filter to laterally squeeze the central lobe of a diffraction limited focal spot. The OEi method was employed in simulations.
Figure 5. The first row in part (a) shows images of the pairs of 10 μm sized holes with separations of $d_{\text{holes}} = 83$ and 65 μm. The remaining pictures depict simulated and experimental intensity distributions resulting from scanning the hole pairs with the Airy disc and an optimized spot. Pictures (b)–(e) show profiles through the ((b), (c)) simulated and ((d), (e)) experimentally acquired intensity distributions for the hole separations of ((b), (d)) $d_{\text{holes}} = 83$ μm and ((c), (e)) $d_{\text{holes}} = 65$ μm.

to determine optimized pupil functions delivering focal spots with a minimized width. Experimentally, encoding these pupil functions on the SLM system, we observed spots with Strehl ratios down to 0.003 matching the numerically simulated data. In future results could be improved using more accurate beam shaping devices and advanced aberration correction methods, eventually also based on OEi optimization.

As an application example, an optimized spot was used to confocally scan in-focus pairs of transmissive holes, yielding a lateral two-point resolution gain of about 1.3 compared to the unobstructed pupil. The experimental results were verified by simulations. In the context of confocal imaging the loss of axial resolution with laterally squeezed focal spots was discussed.

To address this, we proposed utilization of the OEi method in future work to minimize focal spots axially and in 3D. Further future work includes extending the imaging to high NA optics and investigating the practicability for fluorescence and multiphoton imaging.

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