Imaging based on the Extended Nijboer-Zernike (ENZ) formalism

S. van Haver & J.J.M. Braat
Delft University of Technology, IST-Optics Research Group, Delft, The Netherlands

High NA Systems

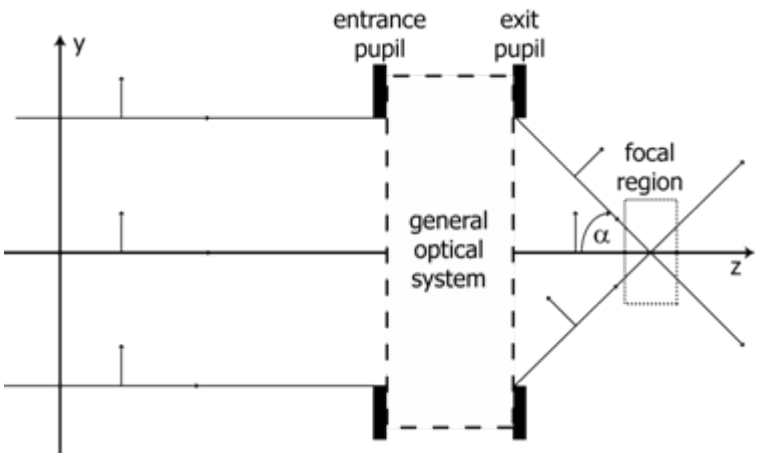
EOS Topical Meeting on Advanced Imaging Techniques, Lille

September 12, 2007

Introduction

The Extended Nijboer-Zernike (ENZ) formalism

- A solution to the Debye diffraction integral for point-like objects at infinity
- Compute the through-focus point-spread function for a general optical system



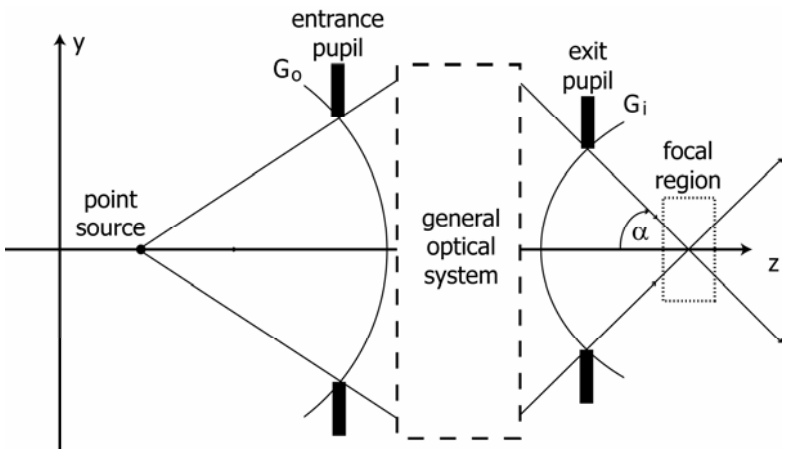
Characteristics:

- Uniform field distribution in the entrance pupil
- All non-uniformity in the exit pupil due to aberrations in the imaging system.

ENZ-based imaging

Modifications needed for general ENZ-imaging

- Allow objects at a **finite** distance



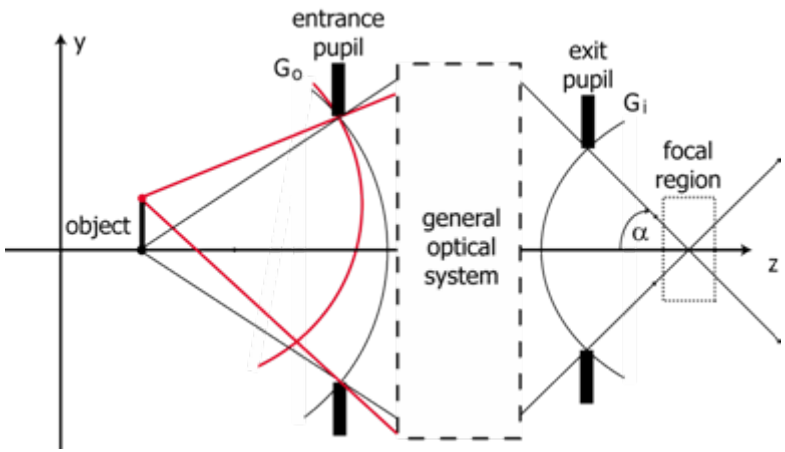
Characteristics:

- Entrance pupil is a spherical surface G_o

ENZ-based imaging

Modifications needed for general ENZ-imaging

- Allow objects at a **finite** distance
- Include **extended** objects



Characteristics:

- Entrance pupil is a spherical surface G_o
- In general a non-uniform field distribution on entrance pupil sphere
- Non-uniformity in the exit pupil results from non-uniformity in the entrance pupil and aberrations in the imaging system

ENZ-based imaging

Representation of the entrance and exit pupil

- In ENZ-theory a pupil is represented by a Zernike expansion:

$$P(\rho,\theta) = \sum_{n,m} \beta_n^m R_n^{|m|}(\rho) \exp(im\theta),$$

where the β's and R's are the Zernike coefficients and polynomials, respectively

ENZ-based imaging

Representation of the entrance and exit pupil

- In ENZ-theory a pupil is represented by a Zernike expansion:

$$P(\rho,\theta) = \sum_{n,m} \beta_n^m R_n^{|m|}(\rho) \exp(im\theta),$$

  where the β's and R's are the Zernike coefficients and polynomials, respectively
- The entrance pupil $P_{entrance}$ should be known

ENZ-based imaging

Representation of the entrance and exit pupil

- In ENZ-theory a pupil is represented by a Zernike expansion:

$$P(\rho,\theta) = \sum_{n,m} \beta_n^m R_n^{|m|}(\rho) \exp(im\theta),$$

  where the β's and R's are the Zernike coefficients and polynomials, respectively
- The entrance pupil $P_{entrance}$ should be known
- The exit pupil P_{exit} follows from $P_{entrance}$ (Abbe-Sine condition) and possibly some deformation introduced by the optical system:

$$P_{exit} = P_{entrance} \times P_{ENZ}$$

  where P_{ENZ} is the pupil transmission of the imaging system constructed from its Zernike coefficients

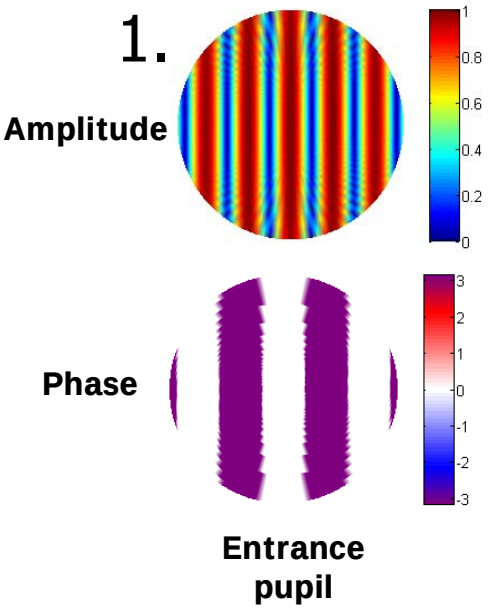
ENZ-based imaging

Computation scheme

ENZ-based imaging

Computation scheme

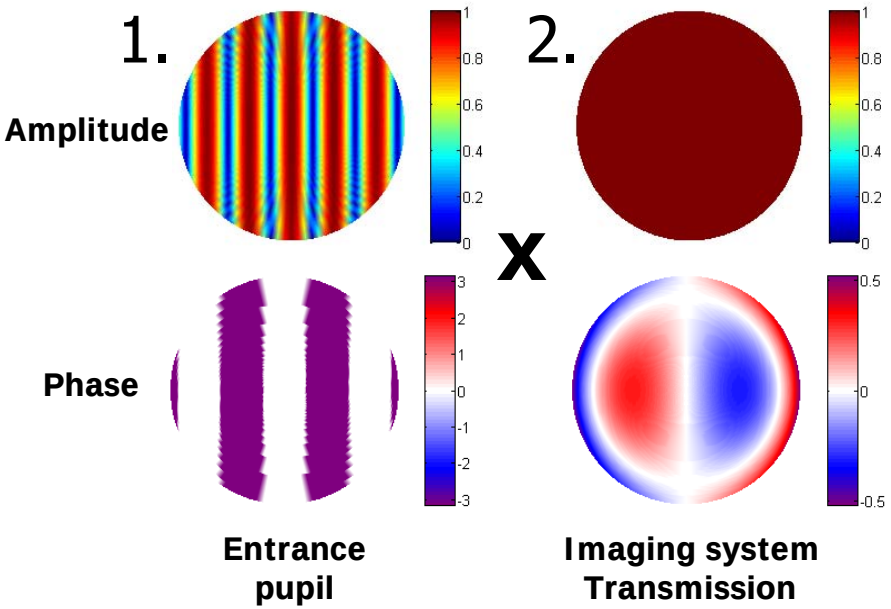
1. Determine entrance pupil distribution



ENZ-based imaging

Computation scheme

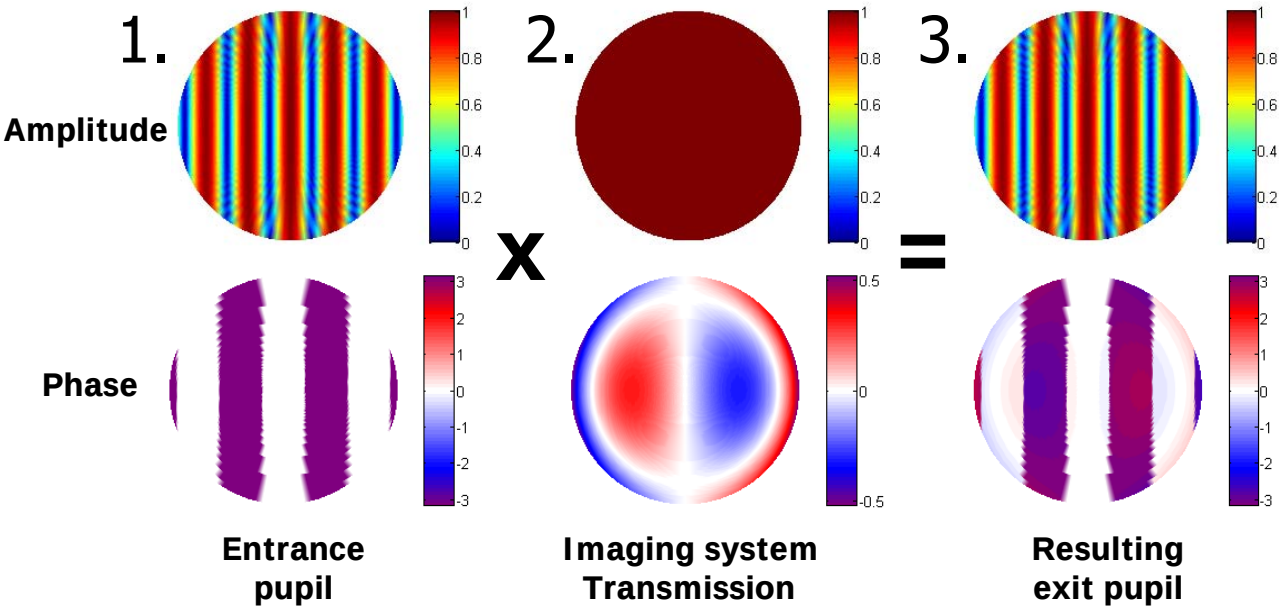
1. Determine entrance pupil distribution
2. Include effects introduced by the imaging system



ENZ-based imaging

Computation scheme

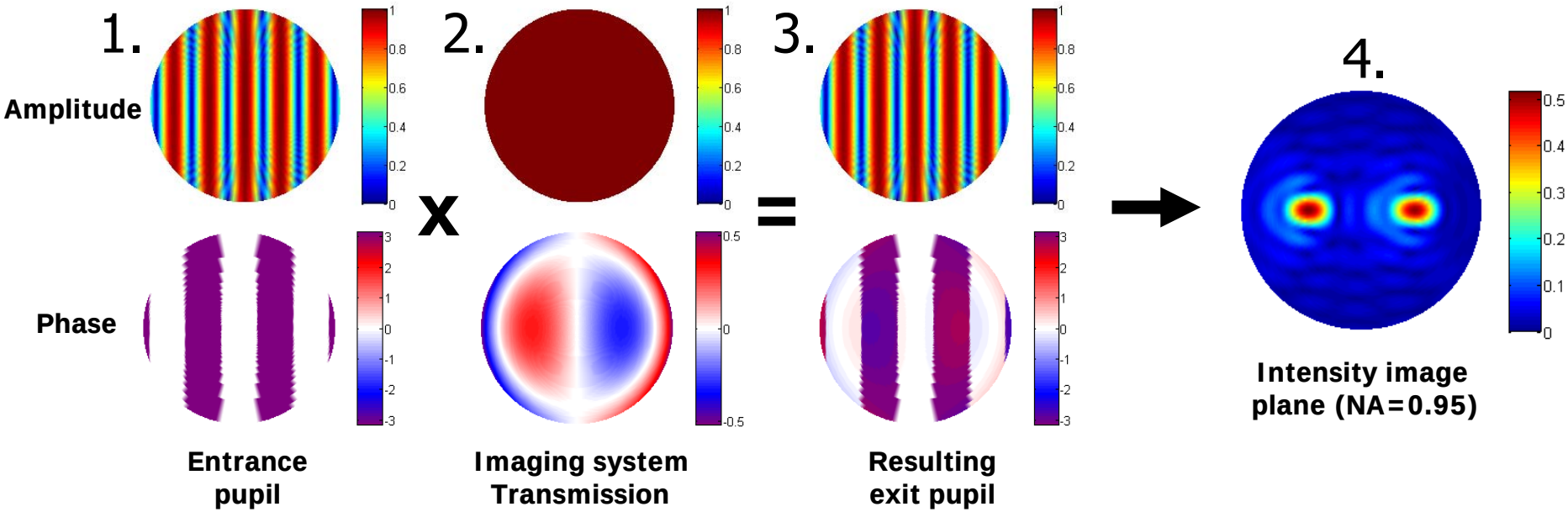
1. Determine entrance pupil distribution
2. Include effects introduced by the imaging system
3. Construct exit pupil and get the Zernike expansion



ENZ-based imaging

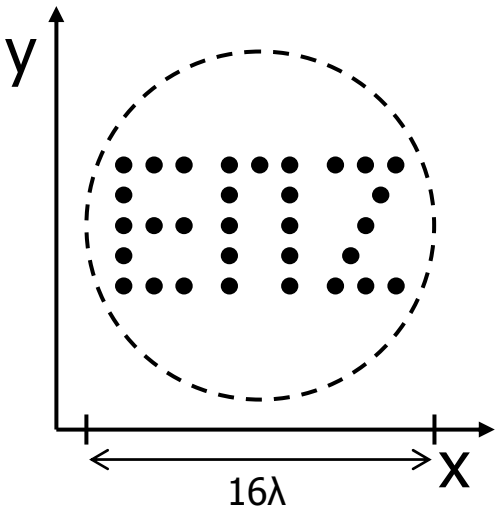
Computation scheme

1. Determine entrance pupil distribution
2. Include effects introduced by the imaging system
3. Construct exit pupil and get the Zernike expansion
4. Get image from the ENZ-formalism



ENZ-based imaging

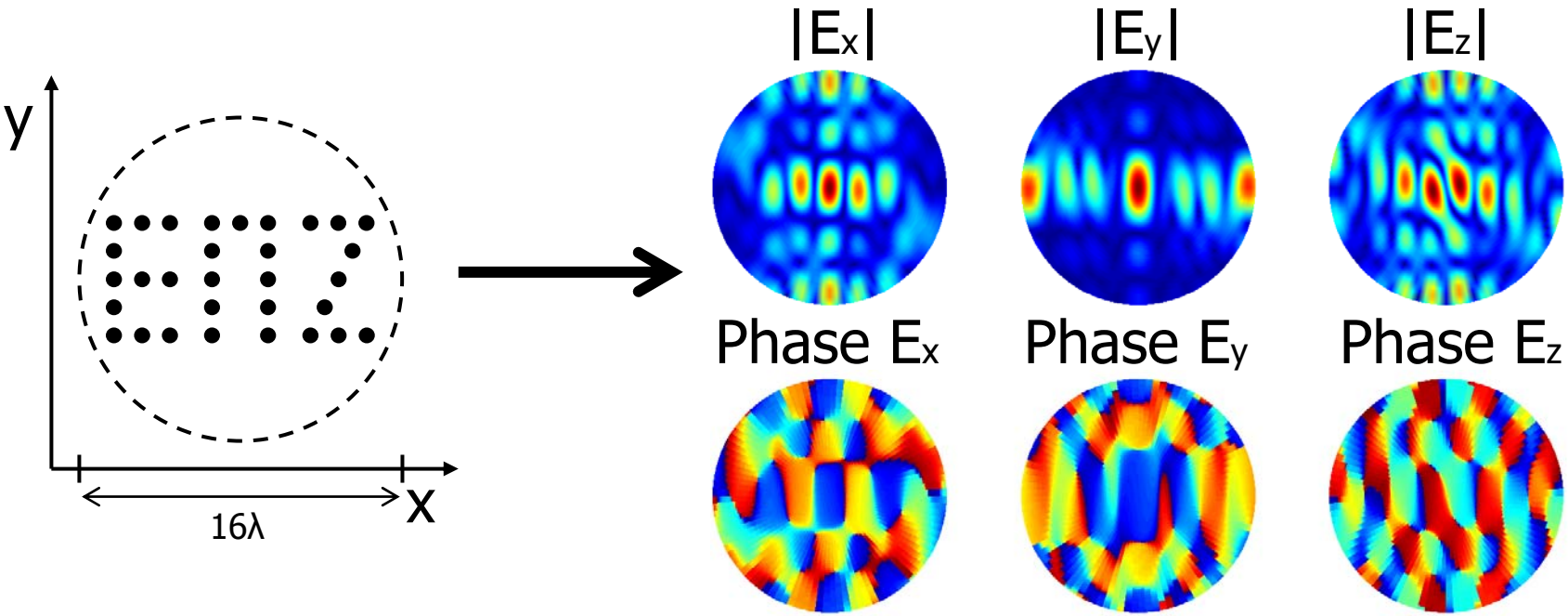
Proof of concept



ENZ-based imaging

Proof of concept

- Calculate the resulting vector field in the entrance pupil



ENZ-based imaging

Proof of concept

- Construct the resulting image in the focal **region** with the ENZ-formalism (NA = 0.95)

in front of image plane

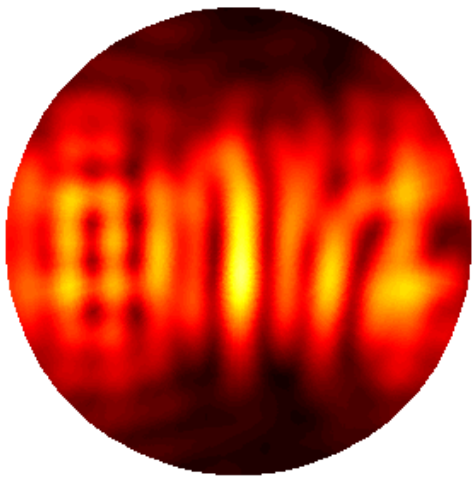
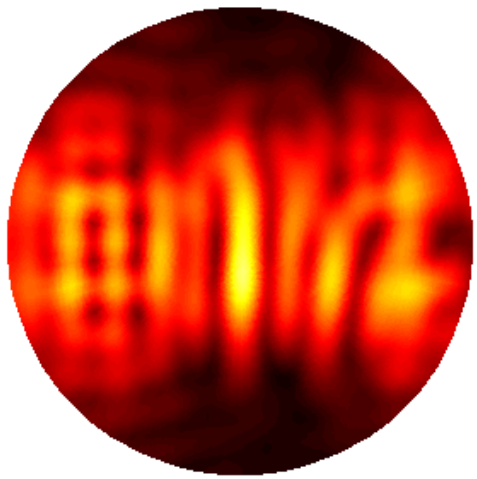


image plane

behind image plane



ENZ-based imaging

Possible applications

- Study aberration effects:

  Assuming that the field distribution in the entrance pupil is known, one can study the effect of aberrations on the image

- New approach to mask-imaging

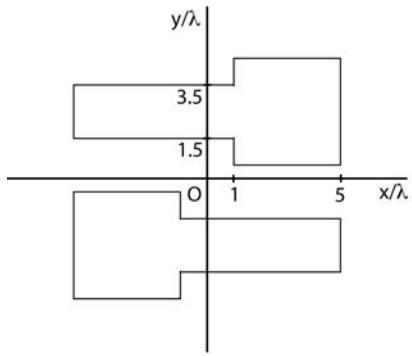
  In combination with an electromagnetic field-solver, one can construct the following mask-image calculation scheme:

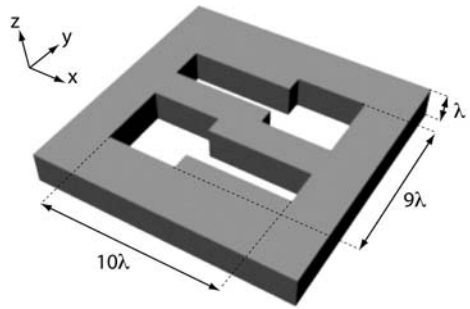
  - Apply an EM-solver to compute the interaction between a mask object and the incident illumination
  - Propagate the resulting near-field to the entrance pupil of the imaging system
  - Represent the field in the entrance pupil in a Zernike expansion and perform ENZ-based imaging to obtain the mask-image

ENZ-based imaging

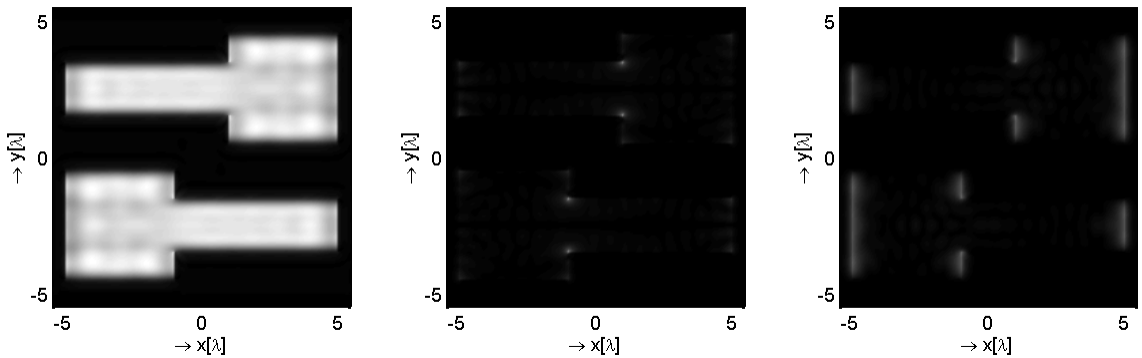
Novel approach to mask imaging: Example

Simplified transmittive mask object





Computed near-field when illuminated by an x-polarized plane wave

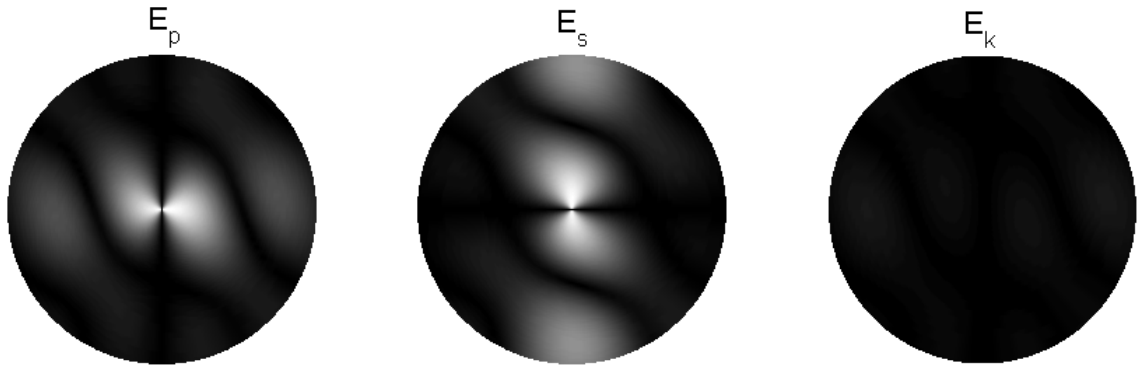


Special thanks to O.T.A. Janssen for his FDTD calculation of the near-field presented above

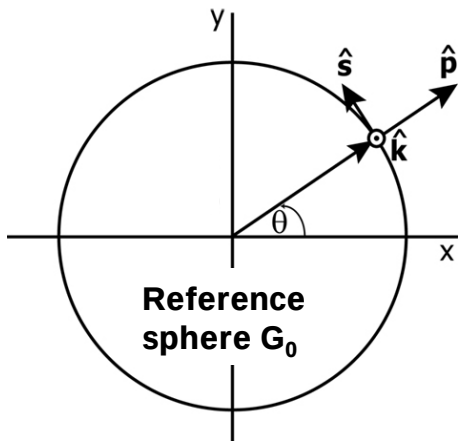
ENZ-based imaging

Novel approach to mask imaging: Example

Electric field in the entrance pupil



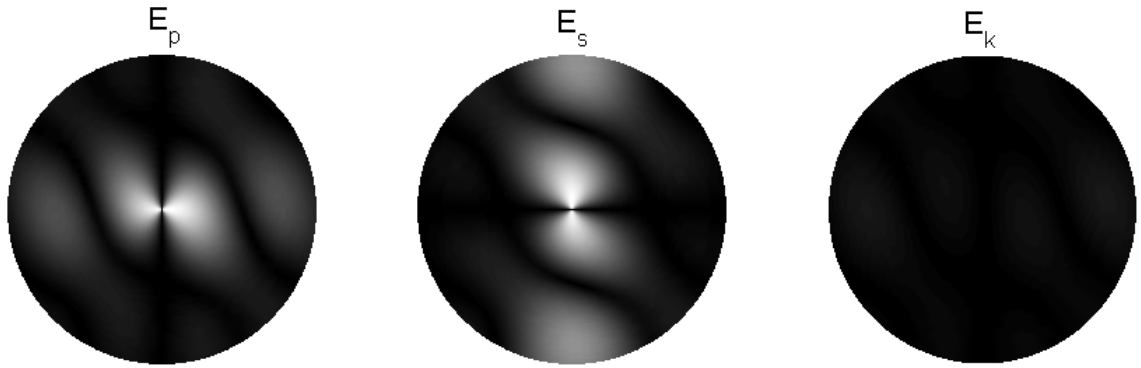
Note: the field is given along the p-, s- and k- unit vectors that allow a straightforward transfer of the field to the exit pupil under the Abbe-Sine condition.



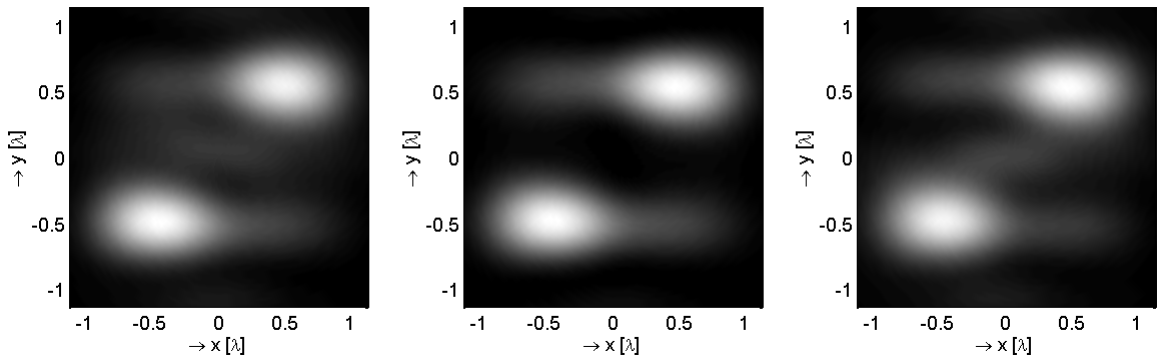
ENZ-based imaging

Novel approach to mask imaging: Example

Electric field in the entrance pupil

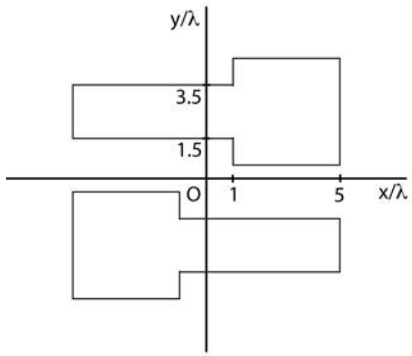


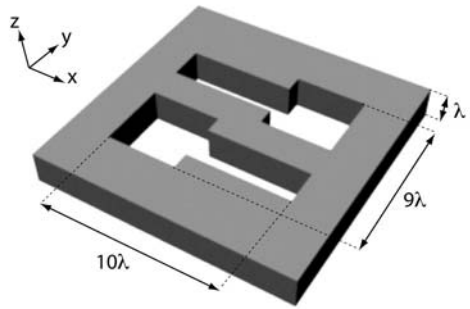
Through-focus image of the mask computed with ENZ-imaging algorithm (NA =0.95)



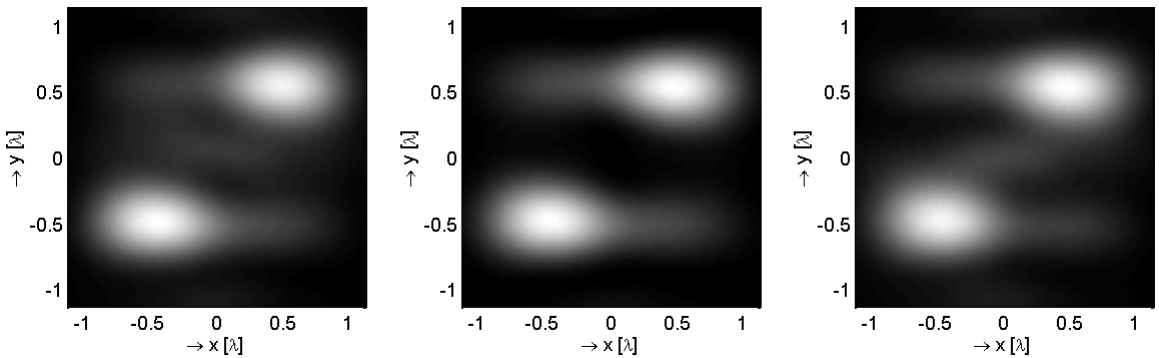
ENZ-based imaging

Novel approach to mask imaging: Example





Through-focus image of the mask computed with ENZ-imaging algorithm (NA =0.95)

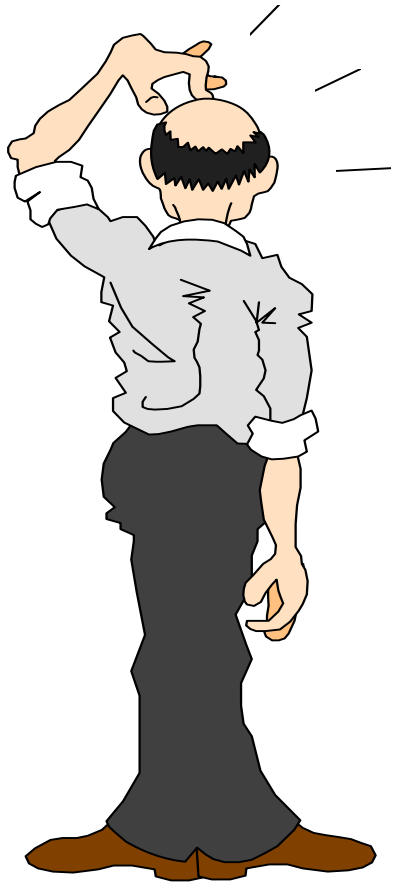


Conclusion & Outlook

- A novel ENZ-based imaging algorithm that computes the image for any given pupil distribution has been introduced
- The ENZ-formalism provides several advantages:
  - Both very fast and accurate calculations
  - Fully vectorial version available, that can deal with high-NA
  - Image information in the focal volume
  - Easy incorporation of aberrations present in the imaging system

- Anticipated application in mask-imaging
- Ongoing research in:
  - ENZ-imaging in a multi-layer
  - Efficient coupling of EM-solvers with the ENZ-imaging algorithm

Questions or remarks?



Http://www.nijboerzernike.nl