# General imaging of advanced 3D mask objects based on the fully-vectorial Extended Nijboer-Zernike (ENZ) theory

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**SPIE Advanced Lithography 2008, Optical Microlithography XXI**

**San Jose, February 27th**

# Contents

- Introduction to the ENZ-theory
- The ENZ-based imaging scheme
- Hopkins vs. ENZ
  - Periodicity
  - Mask topography effects
  - Significance of the on-axis field component
- Conclusions & Outlook

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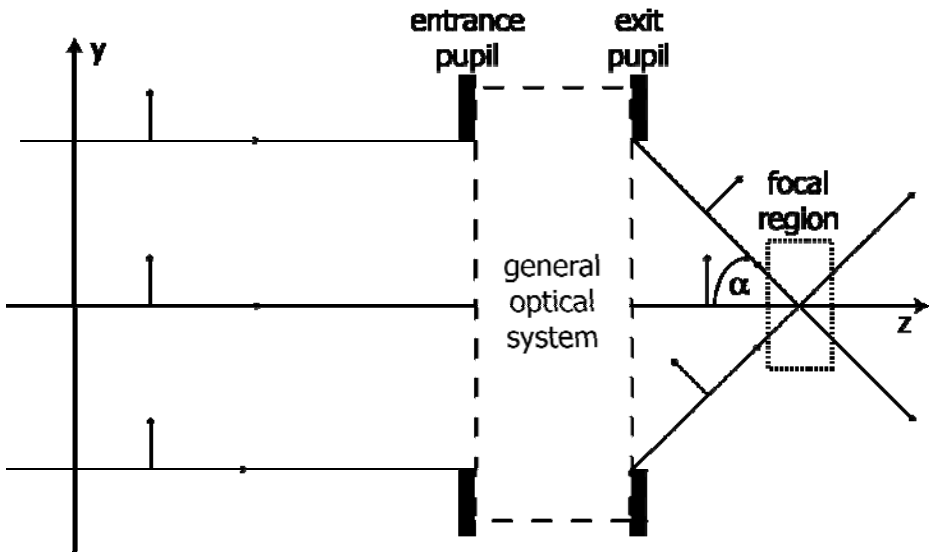
# Introduction

## Extended Nijboer-Zernike theory

Semi-analytic solution to the Debye diffraction integral in case of a point-source at infinity.




Exit pupil distribution → (Debye) → Focal region (image)



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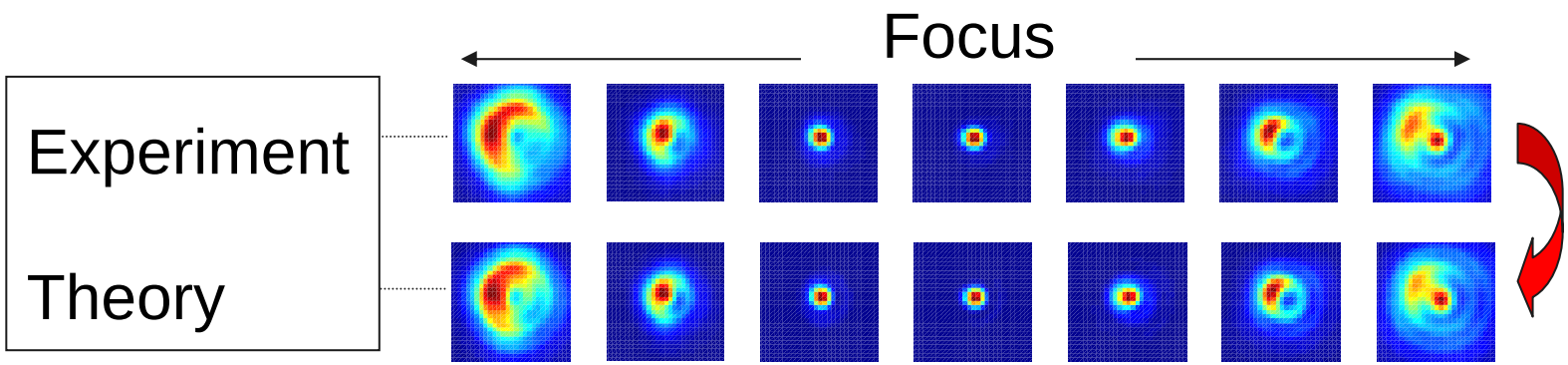
# Introduction

High quality optical system characterization

Observed Intensity = analytic expression
≈ linearized analytic expression
= ∑ β(m,n) x basic-functions

Match experiment to theory:



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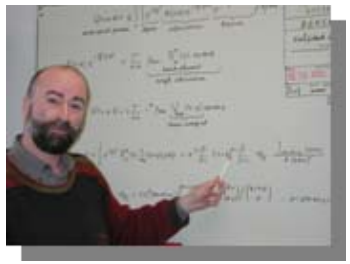
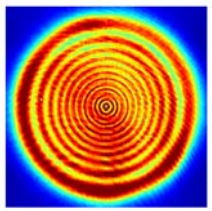
# Introduction

## ENZ historical overview

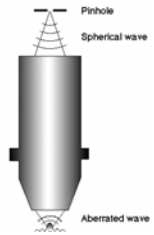
ENZ is born



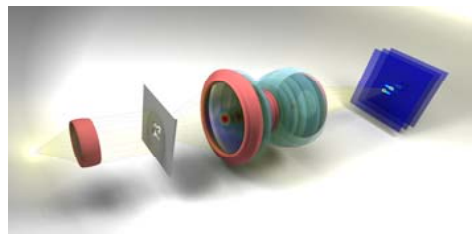
Arbitrary defocus



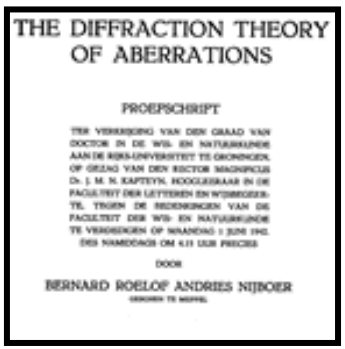
ENZ for lens metrology




ENZ-based imaging



**1942 // 2000 2002 2004 2006 2008**


THE DIFFRACTION THEORY OF ABERRATIONS

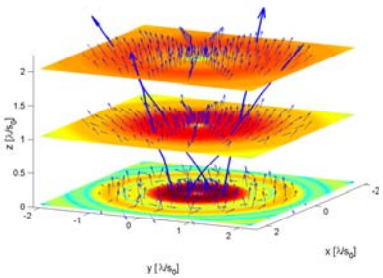
PROEFSCHRIFT

TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKS-UNIVERSITEIT TE GRONINGEN, OP GEZAG VAN DEN RECTOR MAGNIFICUS Dr. J. M. N. KAPTEYN, HOOGLEERAAR IN DE FACULTEIT DER LETTEREN EN WIJSBEGEERTE, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP MAANDAG 1 JUNI 1942, DES NAMIDDAGS OM 4.15 UUR PRECIES

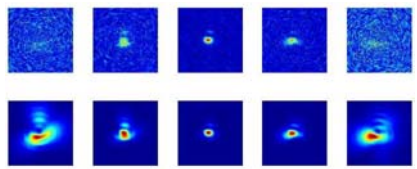
DOOR

BERNARD ROELOF ANDRIES NIJBOER

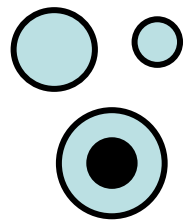
High-NA vector diffraction



General High-NA retrieval



Scaled, Annular pupils





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# Introduction

## Main features of ENZ-theory

- Semi-analytic solution to the Debye diffraction integral based on a fast converging series expansion
- Highly accurate, typically $10^{-6}$ in amplitude
- Both scalar and fully vectorial versions available
- Fast computations possible due to the use of basic functions that can be calculated and stored in advance
- Many focal planes can be calculated in a single computation

# Introduction

Question:

Can we exploit these ENZ-features for (mask) imaging?

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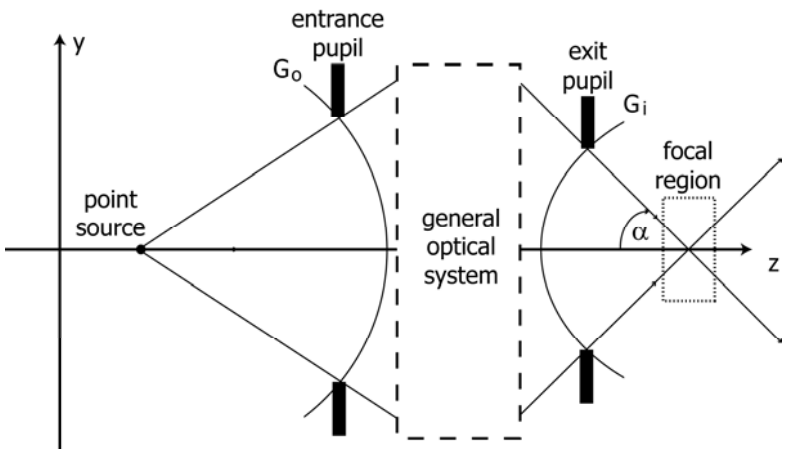
- Conclusions & Outlook

# ENZ-imaging

## Modifications to standard ENZ-formalism

- Allow objects at a **finite** distance




Characteristics:

- Entrance pupil is a spherical surface $G_o$



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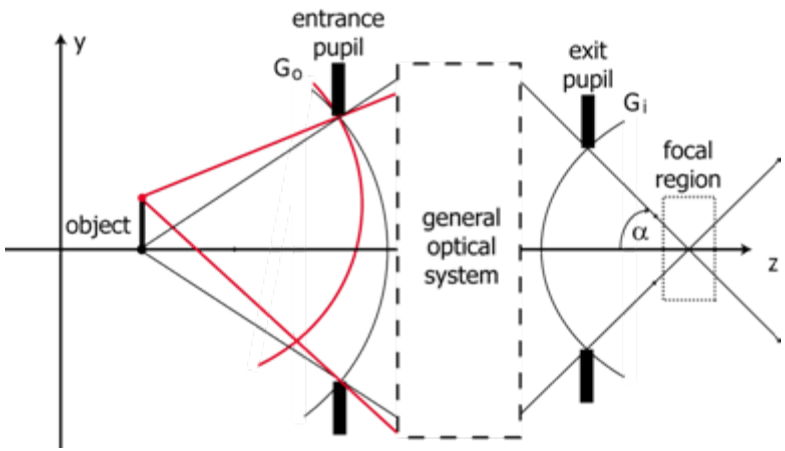
# ENZ-imaging

## Modifications to standard ENZ-formalism

- 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



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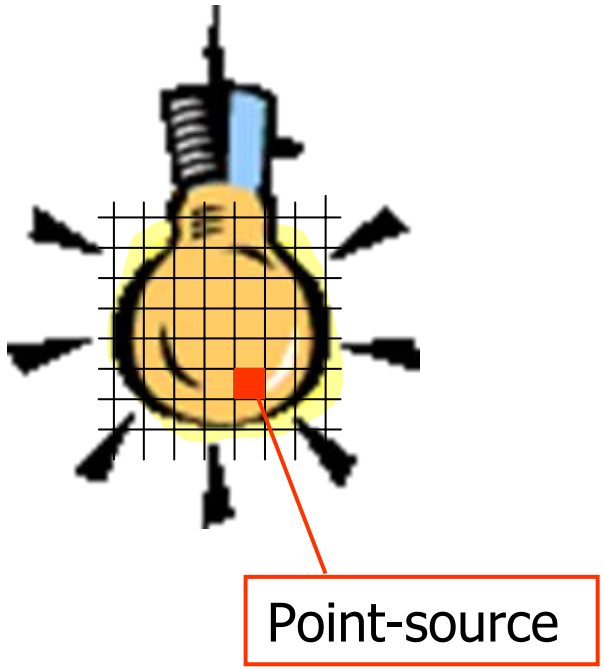
# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources



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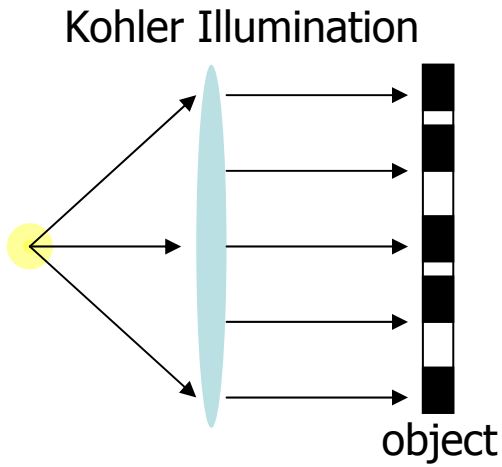
# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources
- A single point-source illuminates object with a plane wave



# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources
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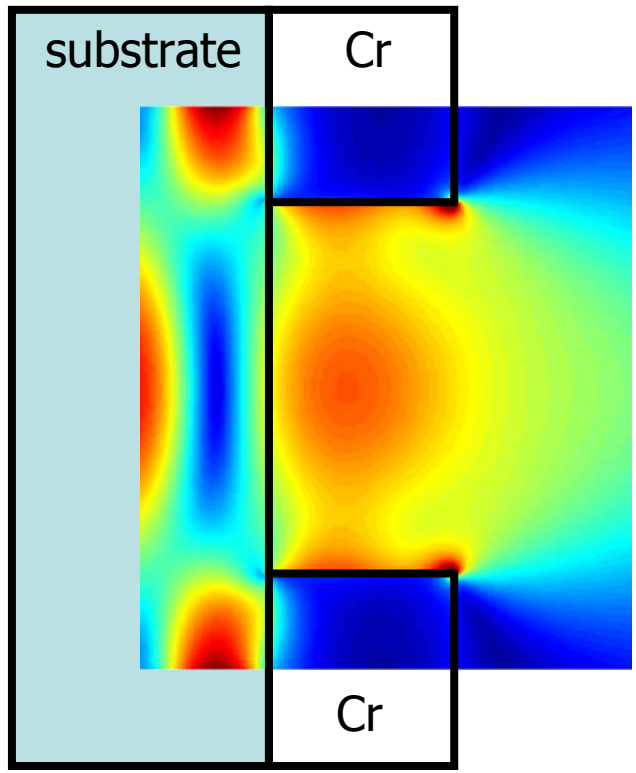
- Compute interaction between plane wave and (mask) object



# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources
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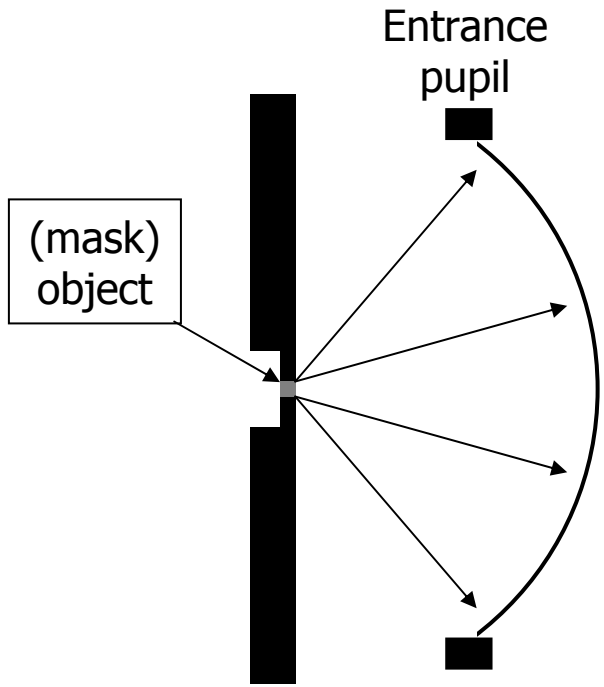
- Propagate field to entrance pupil



# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources
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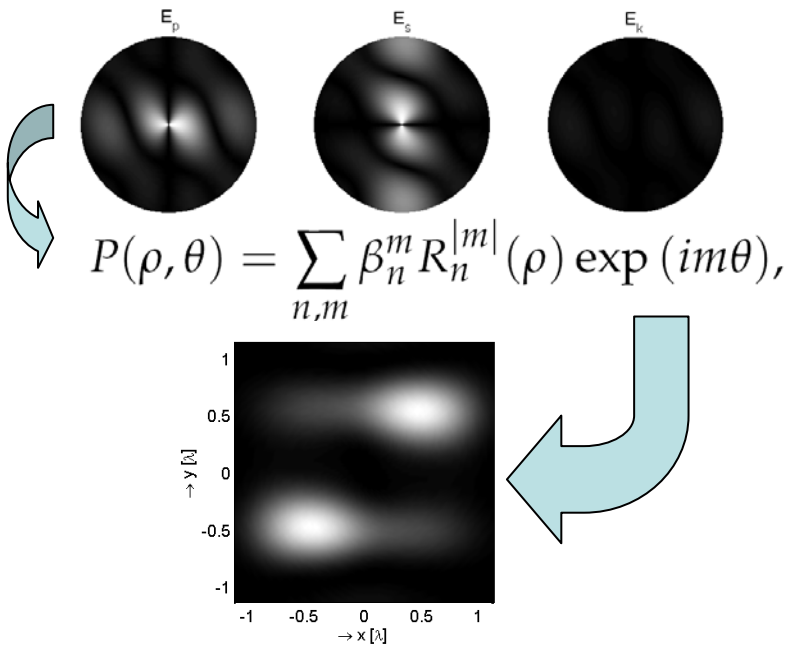
- Propagate field to entrance pupil
- Represent entrance pupil field in a Zernike expansion and use ENZ-theory to generate the image



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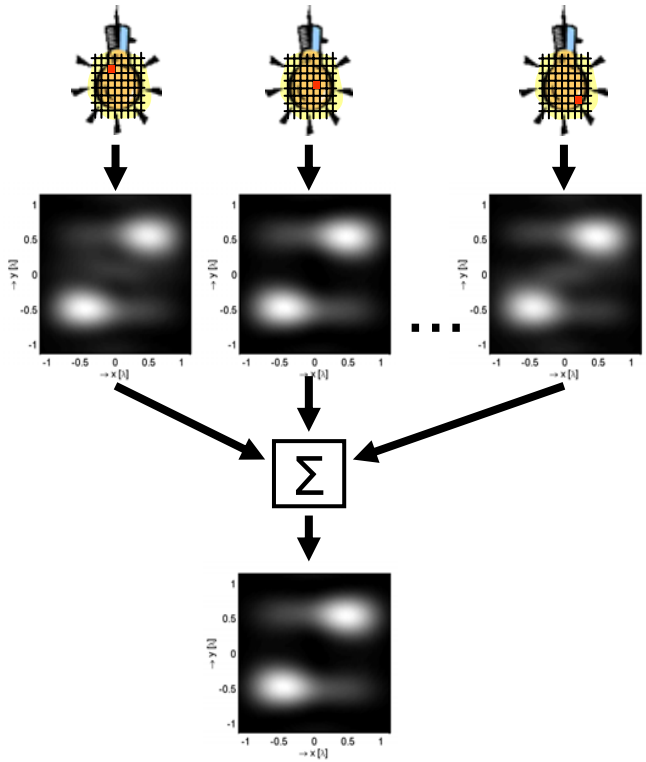
# ENZ-imaging

## An Abbe-based computation scheme

- Regard illumination source as superposition of point-sources
- A single point-source illuminates object with a plane wave
- Compute interaction between plane wave and (mask) object
- Propagate field to entrance pupil
- Represent entrance pupil field in a Zernike expansion and use ENZ-theory to generate the image
- Repeat for all source-points and sum incoherently



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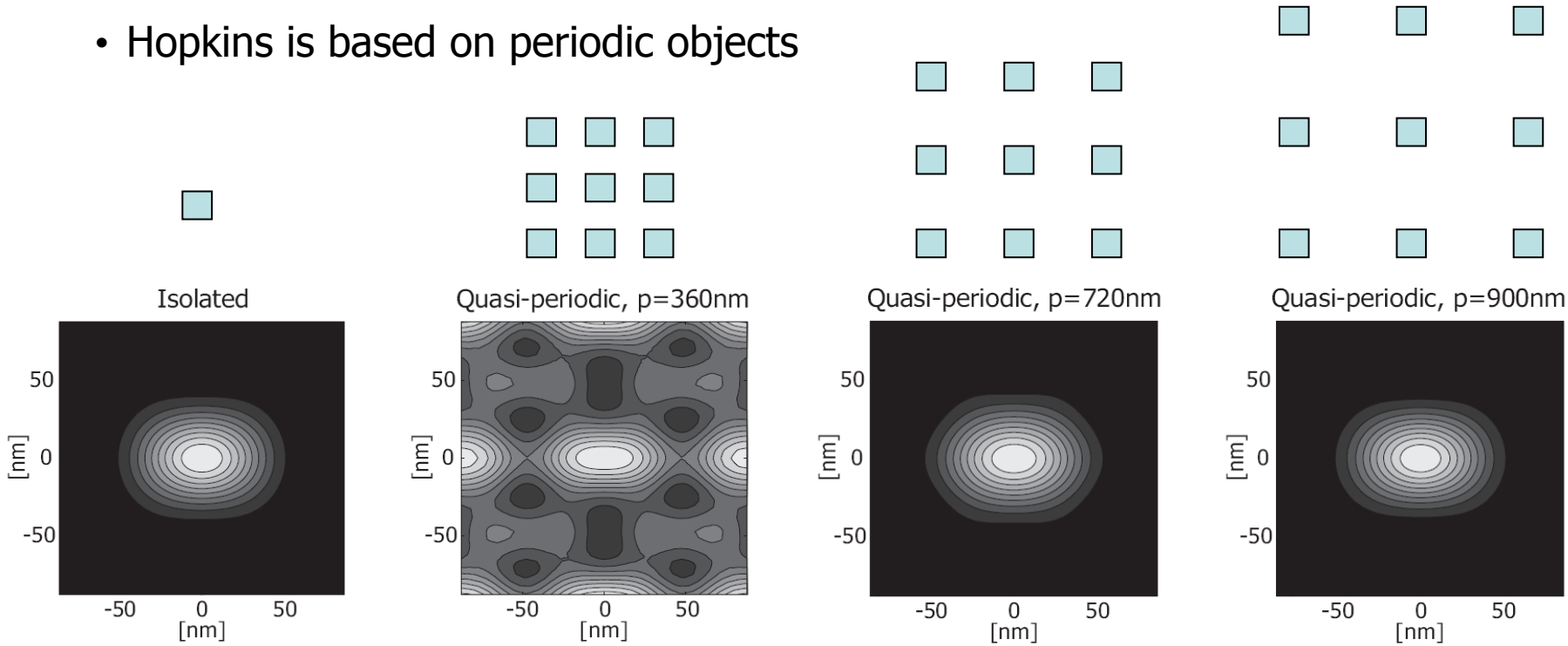
# Hopkins vs. ENZ

## Periodicity

- ENZ acts on isolated objects
- Hopkins is based on periodic objects




**Example: 180nm contact hole imaged with an immersion lithographic system (Reduction=4, NA=2.2, lambda=193nm)**



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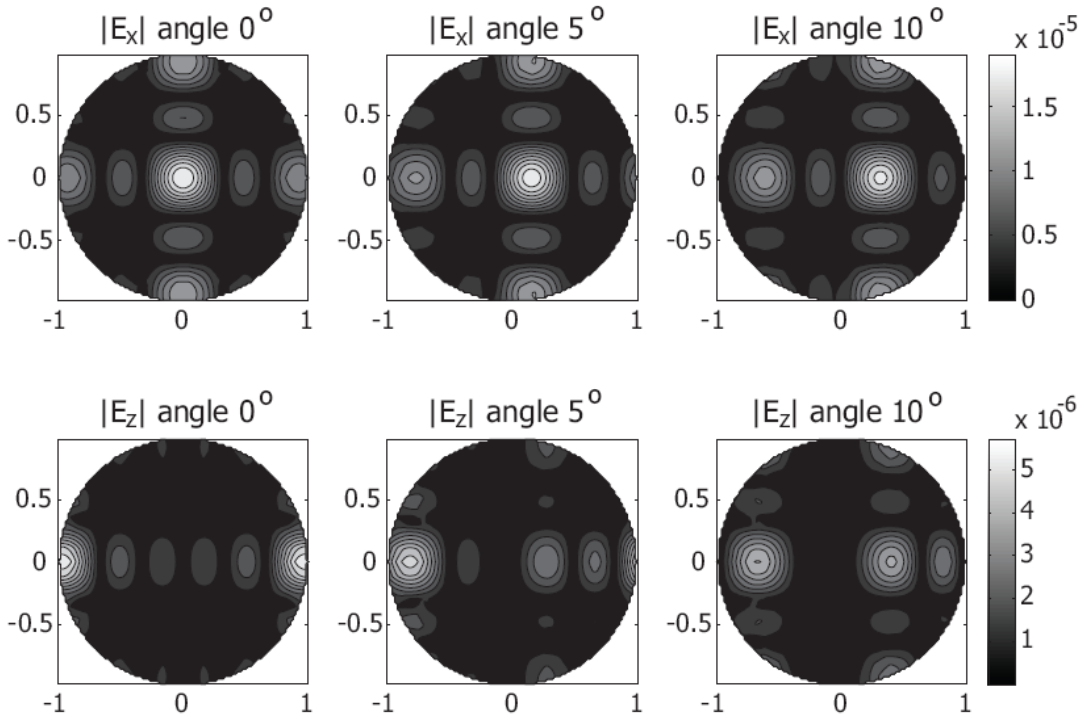
# Hopkins vs. ENZ

## Mask topography effects

- Kirchhoff boundary conditions
- Hopkins approximation



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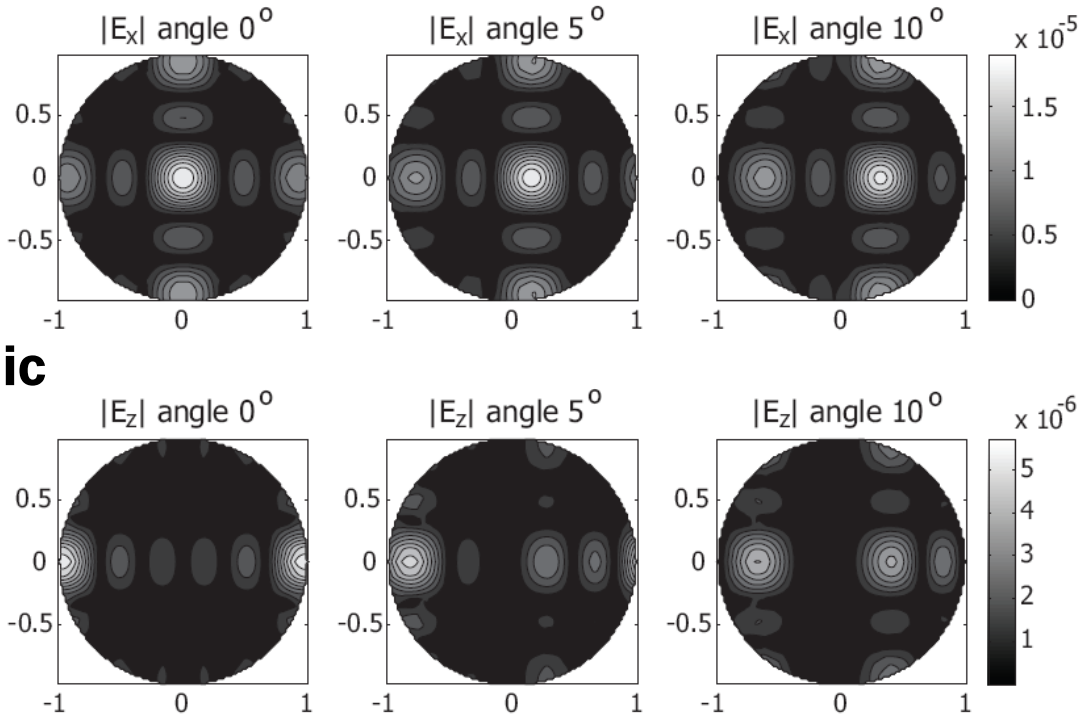
# Hopkins vs. ENZ

## Mask topography effects

- Kirchhoff boundary conditions
- Hopkins approximation

**Present day advanced masks require electromagnetic treatment of the boundary value problem**



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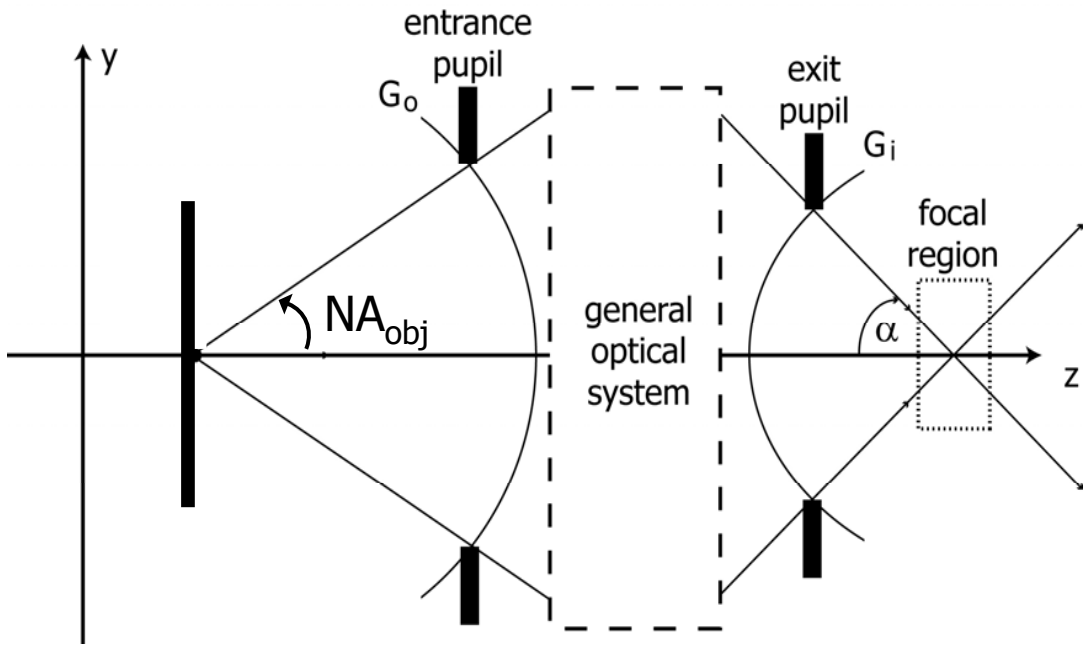
# Hopkins vs. ENZ

## On-axis field component

- Object side NA can be relatively large ($NA_{obj} > 0.2$) for lithographic immersion systems



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# Hopkins vs. ENZ

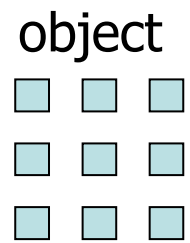
## On-axis field component

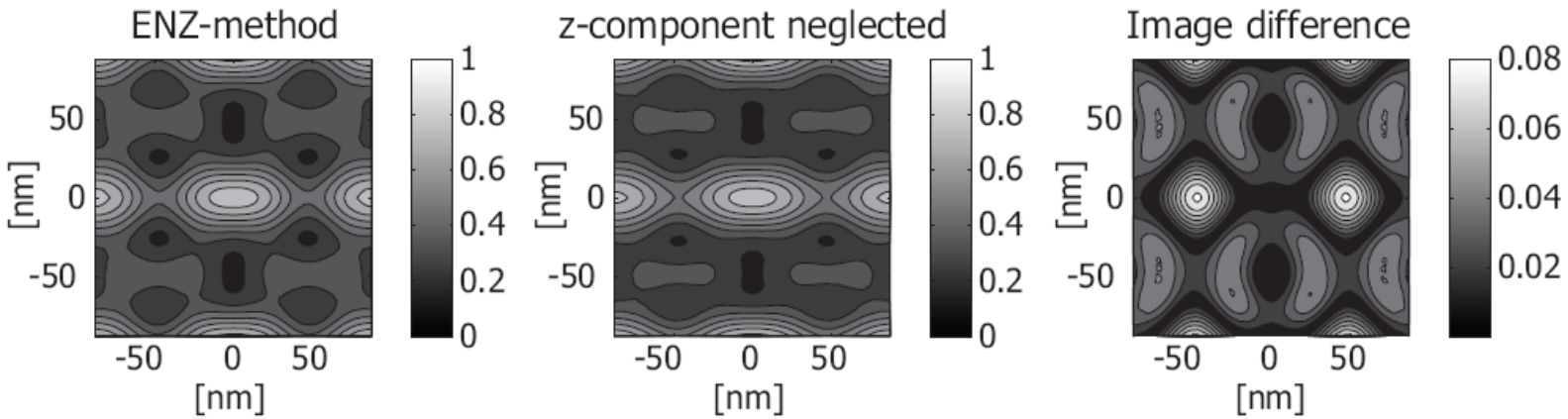
- Object side NA can be relatively large ($NA_{obj} > 0.2$) for lithographic immersion systems
- In this regime the on-axis field component emerging from the (mask) object can give significant contributions to the image

# Hopkins vs. ENZ

## On-axis field component

- Object side NA can be relatively large ($NA_{obj}$ > 0.2) for lithographic immersion systems
- In this regime the on-axis field component emerging from the (mask) object can give significant contributions to the image




**Example: array of 180nm contact holes imaged with an immersion lithographic system (Reduction=4, NA=2.2, lambda=193nm)**



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# Conclusions & Outlook

- Abbe imaging method based on ENZ-theory
  - Naturally treats isolated structures
  - Relies on rigorous EM-solvers at the mask
  - Fully vectorial treatment
  - Potentially fast by the use of basic functions
  - Imaging in many focal planes at once
  - An independent method ideal for benchmarking purposes
- A more direct and accurate approach to lithographic simulations than Hopkins based methods

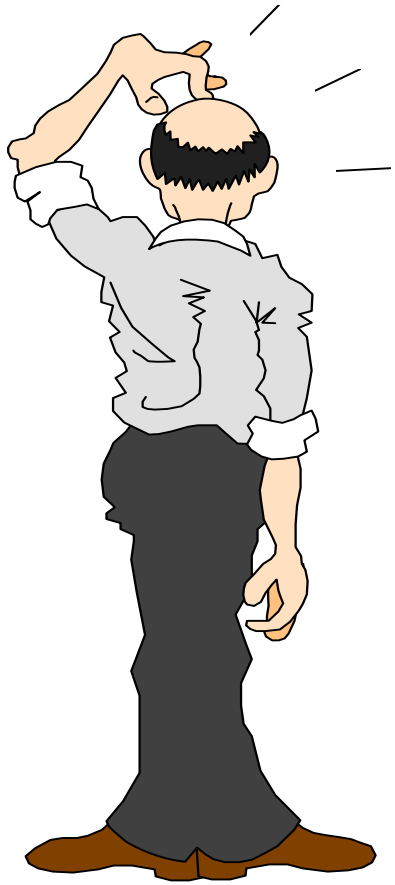
# Conclusions & Outlook

- Ongoing benchmark with existing methods
- Extension of the algorithm to include imaging in a multi-layer (resist)
- Further improve the computational efficiency:
  - coupling between EM-solver and ENZ-theory

**Paper 6924-35:**
**Extended Nijboer-Zernike (ENZ) based mask imaging: efficient coupling of electromagnetic field solvers and the ENZ imaging algorithm**

**Time: 4:30 PM - 4:50 PM**

# Questions?



http://www.nijboerzernike.nl



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