An alternative method for advanced lithographic imaging:
the Extended Nijboer-Zernike formalism

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Contents

• Introduction to the ENZ-theory
• ENZ-based imaging
• The pro and cons of ENZ imaging
• Benchmark with Dr.Litho
• Conclusions & discussion
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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.
Introduction
High quality optical system characterization

Observed Intensity = analytic expression
≈ linearized analytic expression
= \sum \beta(m,n) \times \text{basic-functions}

Match experiment to theory:
Introduction
ENZ historical overview

ENZ is born
Arbitrary defocus
ENZ for lens metrology
ENZ-based imaging


High-NA vector diffraction
General High-NA retrieval
Scaled, Annular pupils

THE DIFFRACTION THEORY OF ABBERRATIONS
PROEFSCHRIFT
BERNARD BOELF ANDREZ NIBBER

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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
Question:

Can we exploit these ENZ-features for (mask) imaging?
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ENZ-imaging
Required modifications to the standard ENZ-formalism

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

Characteristics:
• Entrance pupil is a spherical surface $G_0$
• 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-imaging
Applied assumptions

• Object $<<$ Entrance pupil
  • Fraunhofer approximation can be applied
  • E-field in entrance pupil is perpendicular to normal
  • Only 2 independent field components

• Imaging system satisfies the Abbe-Sine condition
  • Simple relation between entrance pupil and exit pupil
ENZ-imaging
The ENZ-imaging 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 field in the entrance pupil as a Zernike Expansion

Crucial step!
ENZ-imaging
Zernike expansion of the entrance pupil field

Representation of the E-field and Transmission function as a Zernike expansion:

\[
E_{0,x} (\rho, \theta) \ T_I (\rho, \theta) = \sum_{n,m} \beta_{n,x}^{m} R_{n}^{m|}(\rho) \exp(i m \theta),
\]

\[
E_{0,y} (\rho, \theta) \ T_I (\rho, \theta) = \sum_{n,m} \beta_{n,y}^{m} R_{n}^{m|}(\rho) \exp(i m \theta).
\]

Where \( \beta_{n,x}^{m} \) and \( \beta_{n,y}^{m} \) are Zernike coefficients, and \( R_{n}^{m|} \) are the Zernike polynomials.
ENZ-imaging
Zernike expansion of the entrance pupil field
ENZ-imaging

The ENZ-imaging scheme

- Regard illumination source as superposition of point-sources
- A single point-source illuminates object with a plane wave
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- Propagate field to entrance pupil
- Represent field in the entrance pupil as a Zernike Expansion
- Compute image contribution using ENZ-imaging theory

Crucial step!
ENZ-imaging

ENZ-relation between the pupil and the focal region

\[
E_2(r, \phi, f) = \frac{-i \pi f_1 s_0^2}{\lambda [1 - M f_1 / R_1]} \sqrt{\frac{n_0}{n_1}} \exp \left( -\frac{if}{u_0} \right) \sum (-i)^m \exp[i m \phi] \times \\
\left[ \begin{array}{c}
V_{n,0}^m + s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,-2}^m \exp[+2i\phi] + V_{n,-2}^m \exp[-2i\phi] \} \\
-i s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i\phi] - V_{n,-2}^m \exp[-2i\phi] \} \\
-i s_0 \cdot V_{n,+1}^m \exp[i\phi] - V_{n,-1}^m \exp[-i\phi] \\
V_{n,0}^m - s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i\phi] - V_{n,-2}^m \exp[-2i\phi] \} \\
-i s_0 \cdot V_{n,+1}^m \exp[i\phi] + V_{n,-1}^m \exp[-i\phi] \\
\end{array} \right]
\]

Zernike coefficients describing entrance pupil field

ENZ basic functions
ENZ-imaging

The basic functions

\[ V_{n,j}^m(r, f) = \int_0^1 \rho^{j+1} \left\{ \left( 1 - n_1^2 M^2 s_0^2 \rho^2 / n_0^2 \right)^{\frac{1}{2}} + \left( 1 - s_0^2 \rho^2 \right)^{\frac{1}{2}} \right\}^{-j-1} \times \]

\[ \left( 1 - s_0^2 \rho^2 \right)^{\frac{1}{4}} \left( 1 - n_1^2 M^2 s_0^2 \rho^2 / n_0^2 \right)^{\frac{3}{4}} \exp \left[ \frac{if}{u_0} \left( 1 - \sqrt{1 - s_0^2 \rho^2} \right) \right] R_{n,m}^l(\rho) J_{m+j}(2\pi r \rho) \rho d\rho. \]

- Similar integral as found in standard ENZ-theory
- Fast and well converging series expansion available
- Highly accurate
- Independent of the object
ENZ-imaging

ENZ-relation between the pupil and the focal region

\[
E_2(r, \phi, f) = \frac{-i \pi f s_0^2}{\lambda [1 - M f_1/R_1]} \sqrt{\frac{n_0}{n_1}} \exp \left( -\frac{i f}{u_0} \right) \sum_{n,m} (-i)^m \exp[i m \phi] \times
\]

\[
\begin{bmatrix}
\beta_{n,x}^m \\
\beta_{n,y}^m
\end{bmatrix}
= \begin{bmatrix}
V_{n,0}^m + s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i \phi] + V_{n,-2}^m \exp[-2i \phi] \} \\
- i s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i \phi] - V_{n,-2}^m \exp[-2i \phi] \} \\
- i s_0 \cdot V_{n,+1}^m \exp[i \phi] + V_{n,-1}^m \exp[-i \phi] \\
- i s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i \phi] - V_{n,-2}^m \exp[-2i \phi] \} \\
V_{n,0}^m - s_0^2 \left( \frac{n_0^2 - n_1^2 M^2}{2n_0^2} \right) \{ V_{n,+2}^m \exp[+2i \phi] + V_{n,-2}^m \exp[-2i \phi] \} \\
- s_0 \{ V_{n,+1}^m \exp[i \phi] + V_{n,-1}^m \exp[-i \phi] \}
\end{bmatrix}
\]

Zernike coefficients describing entrance pupil field.

Relation between entrance pupil and focal region including:

- High-NA effects, aberrations and immersion imaging.

ENZ basic functions
ENZ-imaging
The ENZ-imaging 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 field in the entrance pupil as a Zernike Expansion
- Compute image contribution using ENZ-imaging theory
- Repeat for all source points and sum incoherently to obtain total image
ENZ-imaging

Image quality vs fitting accuracy in the pupil
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“Pro and cons”
Why (not) use ENZ-imaging

Pro’s:
• A direct treatment of isolated objects
• Point-by-point evaluation of focal region possible
• Potentially far more accurate (fewer approximations, fully vectorial treatment)
• Different model approach is ideal for benchmarking
• Fast for evaluation of many object with equal system settings (basic functions can be calculated and stored in advance)

Cons:
• Immature technology
  • Although potentially fast, still relatively slow
  • Academic tool, not of the shelf applicable
  • Multi-layer imaging still under development
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Benchmark
Compare ENZ-image with Dr. Litho simulations

Isolated contact hole

Through-focus image:

$P = 2.5 \mu m$
$a = 360 \text{ nm}$
$M = 0.25$
$\lambda = 193 \text{ nm}$
$NA = 1.1$
$n_{\text{water}} = 1.44$

$\Delta$Intensity between ENZ and Dr. Litho:
Benchmark

Important observations

- Benchmarking NOT straightforward
  - Fundamentally different input (periodic, isolated)
  - Intermediate results hard to compare (spectrum, E-field)
  - What physics is included and what is neglected?

- Remaining image difference
  - Increases with larger NA
  - Polarization dependent
  - Eternal question: which method is the closest to real systems?
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Conclusions

• ENZ theory allows imaging based on a fundamentally different approach
• ENZ provides a more direct approach in terms of EM fields
• Main characteristics:
  • Isolated objects
  • Rigorous and potentially very accurate
  • Free choice of computed points in focal region
• But it remains an ACADEMIC TOOL (we lack resources to change this!)
Discussion

• Where is ENZ-imaging most useful?
• What additional features would be most useful?
  • Diffusion could be included
  • Image derivatives can be given analytically
  • ...
• Any test-cases available that pose problems to established methods and possibly benefit from an more accurate ENZ-treatment?
• What is the best EM solver to generate the pupil distribution?
• Other questions or comments?
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