A New Design Method for
Extreme Ultraviolet Lithographic Objective

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OUTLINE

- Introduction
- Grouping Design Solution
- Description of Design Method
- Gradual Optimization
- Performance of the Objective
- Conclusions
1. **Constraints in objective design for EUVL**

**Design requirements:**
- Non-obstruction
- High Resolution
- Very low distortion
- Telecentricity on image side
- Total Tack
- Accessible aperture stop
- Working distance
- Low aspheric departure
- Small angle of incidence
- Even mirrors.

**Others:**

- Arc shaped field:
- Field width: 1~2mm, 
  Chord length: 22-26mm,
## Introduction

### 2. Trend of NA of reflective objective

<table>
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<tr>
<th>k₁</th>
<th>HP</th>
<th>45nm</th>
<th>32nm</th>
<th>22nm</th>
<th>16nm</th>
<th>11nm</th>
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<td>NEX 3100</td>
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<tr>
<td>NA0.25</td>
<td>0.83</td>
<td>0.59</td>
<td>0.41</td>
<td>0.30</td>
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<td>NA0.30</td>
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<td>0.49</td>
<td>0.36</td>
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<td>0.54</td>
<td>0.39</td>
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<td>0.41</td>
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</table>

\[ RES = \frac{k₁ \cdot \lambda}{NA} \]

*Need new design strategy!*

*Initial configuration of objective is most important!*

June 14, 2013

EUVL workshop 2013

Yanqiu Li (P54)
3. Design methods of EUVL objective

M.F. Bal, 2003

Paraxial model

Ray matrix

\[
\begin{pmatrix} y_{N+1} \\ u_{N+1} \end{pmatrix} = M \begin{pmatrix} h \\ u_0 \end{pmatrix} + O(3)
\]

Transfer matrix

\[ T_i = \begin{bmatrix} 1 & d_i \\ 0 & 1 \end{bmatrix} \]

exhaustive search of all Independent variables.

C. Wang, 1992

Differential equation

Real Ray Tracing

Assuming mirrors figures (M1, M4) as known parameters

Scott A. Lerner, 2000

Y-Y Diagram

4-mirrors objective

M.F. Bal, 2003

Ray matrix

\[
\begin{bmatrix} y_{N+1} \\ u_{N+1} \end{bmatrix} = M \begin{bmatrix} h \\ u_0 \end{bmatrix} + O(3)
\]

Transfer matrix

\[ T_i = \begin{bmatrix} 1 & d_i \\ 0 & 1 \end{bmatrix} \]

Reflection matrix

\[ R_i = \begin{bmatrix} c & 0 \\ \frac{n_i - n_{i+1}}{c} & n_{i+1} \end{bmatrix} \]

4-mirrors objective

Scott A. Lerner, 2000

Y-Y Diagram

4-mirrors objective

C. Wang, 1992

Differential equation

Real Ray Tracing

Assuming mirrors figures (M1, M4) as known parameters

O. E. Marines, 2006

Saddle Point

Idea for multi-elements
Introduction

3. Design methods of EUVL objective


IDEA about Grouping Design

G1: M1, M2, M3, M4
G2: M5, M6

Detailed design method was not mentioned.
We presented grouping design method with paraxial calculation.

G1, G2 and G3 is design individually, then they are connected to be an initial configuration of Objective.
Problems:

- Connection of each group may cause that pupils are mismatched, and there may be obstruction, because of paraxial approximation.

- We have to make an iterative calculation get an initial objective.
4. What is New in this presentation

- Grouping design method with **off axis real rays tracing**

**Paraxial design**

**Real ray design**

- Pupils are matched exactly, there is no obstruction!
- Real rays are connected perfectly **without** iterative calculation.
- Beam angles can be controlled in each design process.
Before we calculate the initial design parameters, we
1. Grouping strategy

Spherical initial configuration
2. Parameter calculation constraints

**Pupil stop constraint:** If stop is set on a mirror M2, surface parameter (e.g. radius of mirrors) is a function of the pupil or stop position (or diameter).

\[ y_1 = f_a \left( x_1, x_2 \ldots x_n, CA_1, CA_2 \ldots CA_m \right) \]

\( CA_1, CA_2 \ldots CA_m \) are the chief ray tracing data.

\( x_1, x_2 \ldots x_n \) are the given or defined parameters.

\( y_1 \) is the unknown surface parameter.

For example:

M1 radius,

\[ r_1 = h_{z1} \left/ \sin \left\{ \frac{CA}{2} - \frac{\arctan \left( h_{z1} / (-d_1 + z_{z1}) \right)}{2} \right\} \right. \]

**Angle constraint:** \[ \arcsin NA_{obj} < CA = CA_{mask} < 6^0 \]
Non-obstruction constraint:
Surface parameter can be expressed as a function of clearance and the given parameters.

Clearance: the space between the used mirror segment edge and the beam near this mirror:

\[ y_1 = f\left(x_1, x_2 \cdots x_n, \text{CLEAR1}\right) \]

\( x_1, x_2 \cdots x_n \) are the given or defined parameters.

\( y_1 \) is the unknown surface parameter.
3. Parameter calculation constraints

**Conjugation condition:** surface parameter should match the adjacent groups’ characteristic (e.g. whole system meet the pizval sum condition).

\[
\frac{1}{l_1} + \frac{1}{l_1'} = \frac{2}{r_1}, l_2 - l_1' = -d_1, \frac{1}{l_2} + \frac{1}{l_2'} = \frac{2}{r_2} \cdots \frac{1}{l_n} + \frac{1}{l_n'} = \frac{2}{r_n}
\]

**Obj-im conjugation:**

\[
\frac{1}{l_1-enp} + \frac{1}{l_{p1}'} = \frac{2}{r_1}, l_{p2} - l_{p1}' = -d_1, \frac{1}{l_{p2}} + \frac{1}{l_{p2}'} = \frac{2}{r_2} \cdots \frac{1}{l_{pn}} + \frac{1}{l_{pn}'} + \exp = \frac{2}{r_n}
\]

**Pupil conjugation:**

**Magnification:**

\[
\frac{l_n'}{l_n} \cdot \frac{l_{n-1}'}{l_{n-1}} \cdots \frac{l_1'}{l_1} = \beta
\]
3. Parameter calculation constraints

Petzval sum condition

\[ \sum_{i=1}^{N} (-1)^i c_i = 0 \]

Conjugation condition: Middle group should connect the exit pupil of object-side group with the entrance pupil of image-side group.
4. Parameters calculations

Defined parameters:

- **NAO**: Numerical aperture on object side:
  \[ NAO = NA \times |M| \]

- **YOB**: Object height:
  \[ YOB = YIM / |M| \]

- **YIM**: Image height

- **M**: Magnification

- **CA**: Chief ray angle on mask

- **NA**: Numerical aperture on image side

They are obtained from design requirements.
**G1: Object side group**

At first: we choose the adequate $L_1$ and $d_1$ due to the total track and incidence angles constraints.
The mirror radius can be calculated with the defined parameters and constraints:

- **Pupil stop constraint:**

\[
r_1 = \frac{h_{z_1}}{\sin \left\{ \frac{CA}{2} - \frac{\arctan \left[ h_{z_1} / (-d_1 + z_{z_1}) \right]}{2} \right\}}
\]

- **Non-obstruction constraint:**

\[
r_2 = \frac{h_{a_2}}{\sin \left\{ \frac{U_{a_2}}{2} + \frac{\arctan \left[ (CLEAR1 - h_{b_1} + h_{a_2}) / (-d_1 - z_{a_2} + z_{b_1}) \right]}{2} \right\}}
\]

\( r_1 \) : radius of M1,
\( r_2 \) : radius of M2

G1: Object side group
Second: We choose the adequate $WDI$ and $d_5$ due to design requirements and incidence angles constraints.
The mirror radius can be calculated with the defined parameters and the constraint:

**Non-obstruction constraint:**

\[
    r_5 = h_{a5} / \sin \left\{ \frac{U_{a5}}{2} + \frac{\arctan[(\text{CLEAR6} + h_{a5} + h_{b6}) / (-d_5 + z_{b6} - z_{a5})]}{2} \right\}
\]

**Non-obstruction constraint:**

\[
    r_6 = h_{a6} / \sin \left\{ \frac{U_{a6}}{2} - \frac{\arctan[(\text{CLEAR5} - h_{bD1} + h_{a6}) / (-d_5 + z_{a6} - z_{bD1})]}{2} \right\}
\]
The middle group should connect the light path and pupils of G1 and G2 with pupil conjugation constraints.

Parameters given in G1 and G3:

- $\eta_2$: The diameter of G2’s entrance pupil (the diameter of G1’s exit pupil)
- $\eta'_2$: The Diameter of G2’s exit pupil (the diameter of G3’s entrance pupil)
G2: Middle group

-Chief ray angle of incidence in middle group $-U_{z3}$
-Chief ray angle of exitance in middle group $U'_{z4}$
-Upper ray angle of incidence in middle group $-U_{a3}$
-Upper ray angle of exitance in middle group $U'_{a4}$

Configuration parameters:
-Distance between entrance pupil and M3 $L_{z3}$
-Distance between exit pupil and M4 $L'_{z4}$
-Distance between M3 and M4 $d_3$
-Radius of M3 $r_3$
-Radius of M4 $r_4$

To be calculated next.
G2: Middle group

Real ray trace equations under Conjugation conditions:

\[
\sin I_{z3} = \frac{L_{z3} - r_3}{r_3} \times \sin U_{z3}
\]

\[
U_{z3}' = U_{z3} + 2I_{z3}
\]

\[
L_{z3}' = r_3 \times \left(1 - \frac{\sin I_{z3}'}{\sin U_{z3}'}\right)
\]

\[
L_{z4} = L_{z3}' - d_3
\]

\[
\sin I_{z4} = \frac{L_{z4} - r_4}{r_4} \times \sin U_{z3}'
\]

\[
U_{z4}' = U_{z3}' + 2I_{z4}
\]

\[
L_{z4}' = r_4 \times \left(1 - \frac{\sin I_{z4}'}{\sin U_{z4}'}\right)
\]

Then, we can get parameters of \(r_3, r_4, d_3, L_{z3}\) and \(L_{z4}'\)
There are 17 equations and 17 variables including 5 parameters of middle group. (the other 12 variations are defined in appendix).

The configuration of G2 with lower incidence angles on mirrors will be chosen to connect the G1 and G3.

With this method, an initial spherical objective with low incidence angles is obtained.
Then, aspheric coefficients are added gradually, and the system is optimized gradually too. Finally a high quality EUVL objective design is completed.

Variable setting:
- 4th order coefficient
- 6th order coefficient
- 8th order coefficient
- 10th order coefficient
- 12th order coefficient
- 14th order coefficient
- 16th order coefficient
- all the radius
- all the thicknesses
## Performance of the Objective

<table>
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<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>13.5nm</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.33</td>
</tr>
<tr>
<td>A field of view</td>
<td>26mm × 1.5mm</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>4</td>
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<tr>
<td>Total track</td>
<td>1373mm</td>
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<td>Working distance</td>
<td>40mm</td>
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<tr>
<td>Chief ray angle on mask</td>
<td>&lt;6.0°</td>
</tr>
<tr>
<td>Chief ray angle</td>
<td>&lt;22.4°</td>
</tr>
<tr>
<td>Wave front error (RMS)</td>
<td>0.02128 λ</td>
</tr>
<tr>
<td>Distortion (σ = 0.5~0.8)</td>
<td>2.2nm</td>
</tr>
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<td>CD error (σ = 0.5~0.8)</td>
<td>1.2%</td>
</tr>
<tr>
<td>Aspherical departure</td>
<td>&lt; 40um</td>
</tr>
</tbody>
</table>
Conclusions

- A grouping design method using off axis real ray calculation is proposed.

- The method is effective for reducing design variables and controlling incidence angles on reflective mirrors.

- With this method, the initial configurations of objective is suitable for further optimization to meet the requirements
Appendix

Parameters of chief ray:

\( I_{z3} \) Incidence angle of M3
\( I_{z4} \) Incidence angle of M4
\( U'_{z3} \) Image-side aperture angle of M3
\( L'_{z3} \) Image-side intercept of M3
\( L_{z4} \) Object-side intercept of M4

Parameters of upper ray:

\( I_{a3} \) Incidence angle of M3
\( I_{a4} \) Incidence angle of M4
\( L_{a3} \) Object-side intercept of M3
\( L'_{a3} \) Image-side intercept of M3
\( L_{a4} \) Object-side intercept of M4
\( L'_{a4} \) Image-side intercept of M4
\( U'_{a3} \) Image-side aperture angle of M3
Acknowledgment

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Thanks for your attention!