Advanced Modular Illuminators for high image quality optical systems.

Lev Ryzhikov and Yuli Vladimirsky

Keywords: Köhler illumination, Critical illumination, aberrations, field uniformity, ellipticity, telecentricity, vignetting,

Abstract

Demand for High- and Hyper-NA (numerical aperture) High image quality tools including immersion systems is growing. This demand translates in necessity to design illuminator with large NA to provide all desired illumination modes. To realize sufficient image quality low levels of projection optics residual aberrations are required. Consequently, more attention should be paid to aberration correction in illuminators to ensure optimal performance of High- and Hyper-NA high quality lens system. This leads to dramatic increase of laser illumination system (LIS) optics complexity.
In order to aid designs of systems providing optimal illumination conditions without degradation of LIS performance, we are presenting design methodology, based on modular configuration.
In presented approach we identify three groups of modules or optical elements essential for advanced illuminator: transform lenses, relay systems, and étendue modifiers. Implementation of Köhler scheme as a transform lens system, Critical illumination as a relay lens system, and multi-aperture refractive and diffractive arrays as étendue modifiers will be discussed.

1. Introduction

Most of the advanced high quality optical systems have numerical aperture (NA) greater then 0.9 for the dry and <1.35 for the immersion system with typical de-magnification of 4X. For realization of high resolution nodes advanced masks, utilizing different RET (mask enhancement techniques) and OPC (optical proximity correction) enhancements, such as clear and attenuated phase shifters, bias, auxiliary features and etc, are used more and more often. To aid these enhancements a multitude of illumination modes with specialized and sophisticated partial coherence (**$PC=NA_{ill}/NA_{PO}$**) schemes is implemented. Those include low PC, aggressive annular, dipole, quadruple, and hybrid illumination patterns. The maximum values of PC required are reaching 0.95-1. This means that maximum illumination NA, provided by LIS (laser illumination system) at the reticle plane, should be in the 0.22-0.33 range. This requirement determines illuminator design. In order to provide exposure field with high uniformity, low pupil ellipticity, decent telecentricity and minimum transmission loss, more complex optical illuminator system should be used with minimum aberration. To achieve those requirements in LIS of the high image quality tools, the Köhler [1] and critical illumination [1] schemes are used. To simplify and make illuminator design process more effective authors developed and patented a modular approach [2],[3]. It is shown that to some extend critical illumination schemes can be realized using Köhler illumination modules.

2. Basic high image quality system structure and modules

Major optical modules of the high image quality system are shown in Figure 1. The modular structure of illumination system has been discussed to a certain degree in previous contribution [4].
Light, emitted from a laser (usually eximer laser), passes through a beam delivery system. Expanded and homogenized beam enters into the Laser Illumination System – LIS, the Pupil Defining optical module (PDM), which consists of Pupil defining element (PDE) and transform lens (condenser) **C1**. This module is responsible for generation of required angular (PC) illumination mode settings and facilitates to achieving spatial illumination uniformity of the exposure field. **C1** condenser lens can have fixed or variable focal length. If **C1** focal length is variable, different partial coherence PC values (**PC**) can be achieved by varying condenser focal length. If condenser has fixed focal length, partial coherence change can be achieved by changing PDE.
The following module, FDM (Field Defining optical module), is responsible for illumination field formation and allows to achieve required dose uniformity, ellipticity and telecentricity of illumination modes. This module includes Field defining element (FDE) and transform lens (condenser) **C2**,
The illumination field shape is controlled by a delimiter **D** and is re-imaged by a Relay (with an aperture stop **AS)** onto the reticle plane **R**. The Pupil and Field defining optical elements could utilize diffractive or refractive optical structures.
Last and most critical from imaging point of view part of the high image quality tool is Projection optics (PO). Projection optics produces an image of a reticle onto wafer plane. Three most important parameters of a PO, such as numerical aperture, magnification and wafer field size, are drivers for illuminator design. Complexity of the illuminator strongly depends on those parameters: bigger NA and field size values require more complicated illuminator design, especially in conjunction with large magnification.

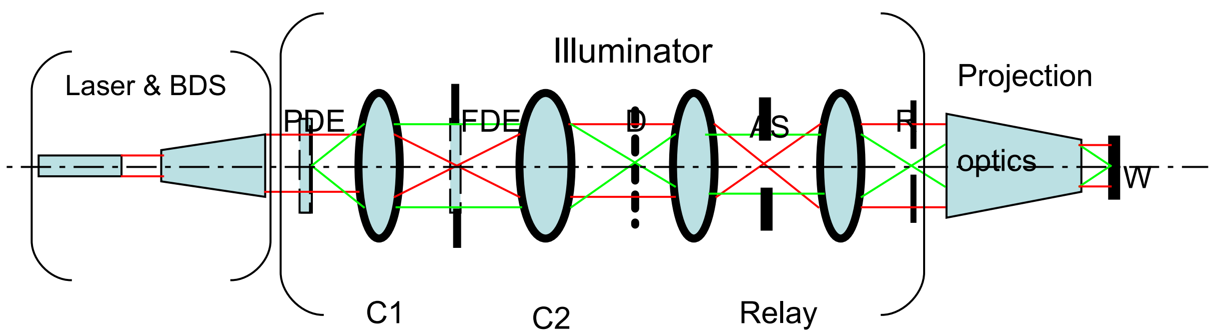

Figure 1 Optical schematic of the typical Litho tool

For better description of Illuminator functionality several important optical plane are explicitly labeled. Five major planes are shown in Fig. 1. Those are: PDE plane, FDE plane, Delimiter plane, Relay aperture stop plane and Reticle plane. Theoretically all those planes optically conjugate ether with wafer plane of the PO or with PO pupil plane. Particularly PDE, Delimiter and Reticle plane are optically conjugate with wafer plane and all other are conjugate with PO pupil. All illuminator major optical modules located between those planes. The proposed illuminator design methodology based on individual optical module functionality and essential level of module performance in other words each module should be designed and corrected individually (aberration, telecentricity etc) this is the first step of the illuminator design process with further modeling whole system and if it necessary changing modules designs when whole illuminator system performance is evaluated. Typical LIS consists on two types of optical modules: system utilizing Kohler illumination scheme and system utilizing Critical illumination scheme.

2. Optical modules realizing Köhler illumination scheme.

The transform lenses or condensers represent Köhler illumination scheme. In this case each source point of radiation illuminate whole field [1]. Figure 2 show typical transform lens schematic. Pupil located in front focal point and imaged in infinity. All images overlapped on the illuminated field. To define first order optical parameters some simple equations can be written:

$$Y' = f' \cdot \tan(\alpha); \quad R = f' \cdot \tan(\beta) \quad (1)$$

Here ***f'*** **–** is condenser focal length; ***Y'*** **–** is half-height of illuminated field; ***R*** **–** is pupil radius; ***α***, ***β*** **–** are angular characteristics of the incident and refracted beams respectively.
Also total length of the condenser ***L*** should be mentioned here. This is very important packaging parameter. As we see from fig. 2 in simple case (one lens system) ***L=2· f';*** but often condenser need to be packed in much shorter space. This condition drives complexity in condenser design. Table 1 gives approximate number of lenses vs. packing length.

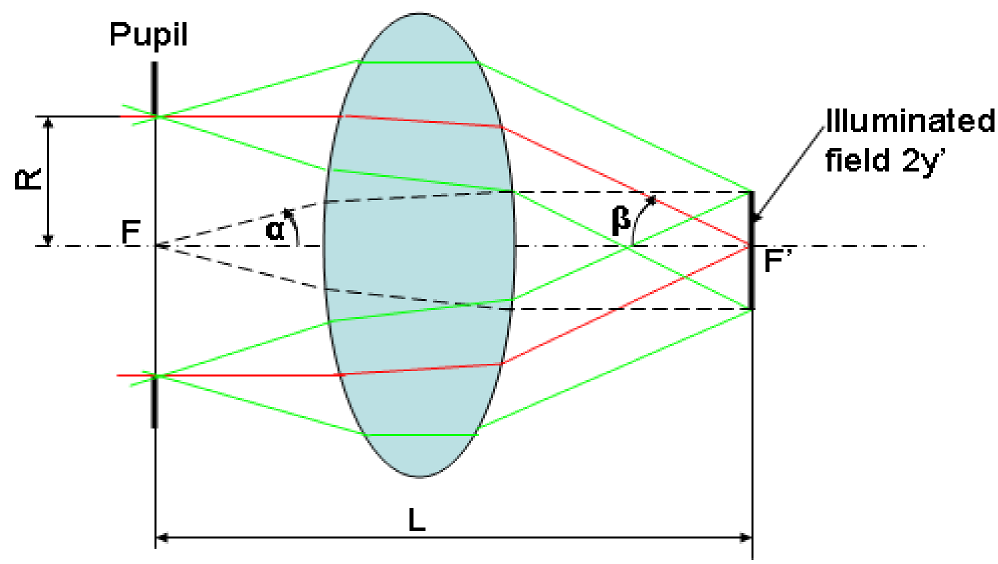

Figure 2. Optical schematic of Transform lens

Table 1 Condenser packaging conditions

Number of lenses	Condenser length
1	2 *f'*
2	(1.1-1.3) *f'*
3	(0.4-1) *f'*
4	(0.25-0.4) *f'*

Complexity of the condenser lens also strongly depends on other parameters such as F-number, NA values, degree of telecentricity correction, allowed image field illumination non-uniformity; blur spot diameter (which basically depends on residual aberration) and distortion. High level of telecentricity correction and small illumination non-uniformity at the image plane can be achieved if the residual aberration is small enough. If the optical system were aberrated, rays would be intercepted in the image plane far from ideal location. As a consequence, additional image field overfill and light loss [2] will be present, as well as field illumination uniformity will be insufficient to meet lithographic requirements. Most common condensers consist of two or more lenses. In first order calculation the optical power of a two-lens condenser is [5]:

$$\Phi=\Phi_1+\Phi_2-d_{1,2}\cdot\Phi_1\cdot\Phi_2; \qquad \textbf{(2)}$$

Here, $\boldsymbol{\Phi = 1/f'}$**-** is an optical power of the condenser; $\boldsymbol{\Phi}_1$, $\boldsymbol{\Phi}_2$ – are an optical power of the condenser lens 1 and 2 respectively; $\boldsymbol{d_{1,2}}$ **–** distance between condenser lenses. Expression (2) can be used for 2 lens systems with NA<0.2.
For more complicated system and large NA (3 or more lenses) the lens powers and distances between the lenses have to be considered. For instance, for three lenses (Figure 3) the following equation presents condenser optical power []:

$$\Phi=\Phi_1+\Phi_2+\Phi_3-d_{1,2}\Phi_1(\Phi_2+\Phi_3)-d_{2,3}(\Phi_3+\Phi_1)+d_{1,2}d_{2,3}\Phi_1\Phi_2\Phi_3; \qquad \textbf{(3)}$$

When distances $\boldsymbol{d_{i,i+1}}$ in (2) and (3) are small $\boldsymbol{d_{i,i+1}\rightarrow 0}$ optical power of a lens system becomes just sum of lens powers:

$$\Phi=\sum\Phi_i; \qquad \textbf{(4)}$$

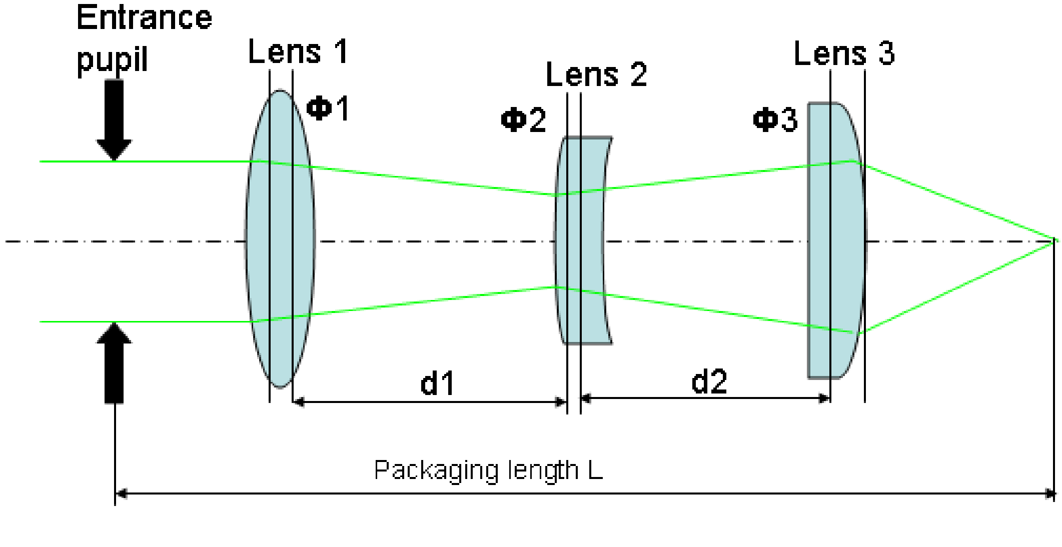

Figure 3. Optical schematic of 3 lens condenser

3. Optical modules realizing Critical illumination.

In the Critical illumination method each point in the source plane is imaged to a corresponding point in the illumination plane [1]. Typical optical module realizing this type of illumination is an optical Relay. Figure 4 shows a simple two-lens relay optical schematic.

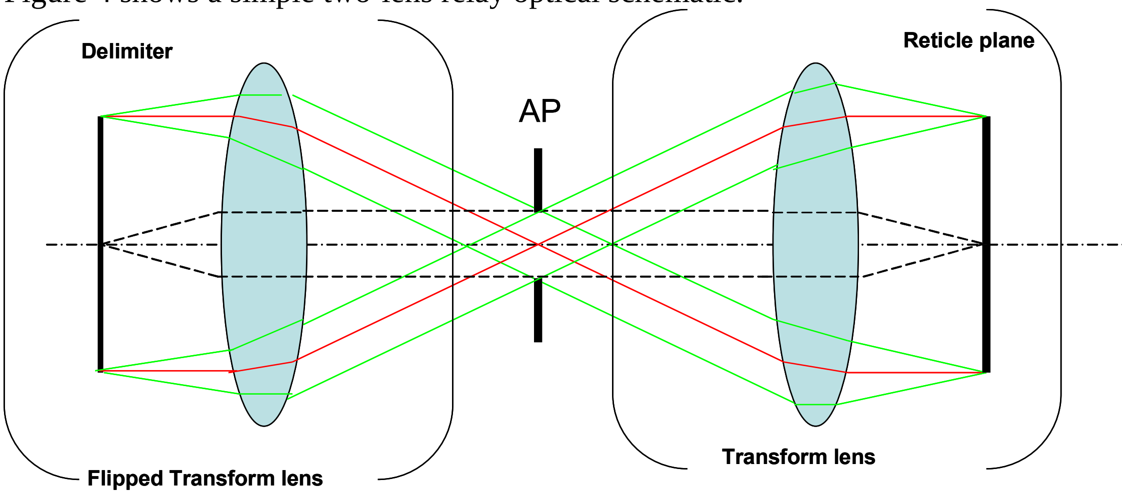

Figure 4. Optical schematic of Relay lens

The first order parameters for Relay lenses are: magnification (***M***), object plane size (***Y_1***), image plane size (***$Y' = Y_2$***), and numerical apertures - at the object plane ***NA_1*** and at the image plane ***NA_2***. In this case expression (2) can be used and modified to describe a relay as an afocal system:

$$\Phi_{Critical}=0;\ \ \Phi_1+\Phi_2-d_{1,2}\cdot\Phi_1\cdot\Phi_2=0;\ \ d_{1,2}=f_1+f_2; \qquad \textbf{(5)}$$

With magnification

$$M=Y_{IM}/Y_O=NA_O/NA_{IM}=f_2/f_1; \qquad \textbf{(6)}$$

Important advantages of afocal arrangements are: simpler and more effective assembling and alignment procedures compared with other systems, as well as better telecentricity. Minimization of non-telecentricity, defined as a deviation of principal rays from being parallel to the optical axis, is translated in minimization of overlay errors in high image quality system even within depth of focus. Introducing distances ***a_1*** and ***a_2*** from object and image planes respectively to corresponding lenses and using (5) an (6) we can find

$$a_2=f_2+M^2\cdot(f_1-a_1);\ \text{ or in a symmetrical form }\ \frac{f_2-a_2}{f_1-a_1}=-M^2; \qquad \textbf{(7)}$$

Clearly, that when $a_2>f_2$, than $a_1<f_1)$. When an object is placed in the front focal plane of the object lens $a_1=f_1$, then we have image formed in the back focal plane of the image lens $a_2=f_2$.

4. Aberration in optical system

Usually relay illuminated reticle and located after all transform lenses just before projection optics. Correction aberration in relay should in some decent level because relay lenses re-image delimiter onto reticle plane and provide illumination for the reticle.

Main parameter for aberration correction is blur spot diameter. In advanced high image quality optical system NA at the wafer plane is 1.2-1.35. In this case Relay should have NA = 0.325. This is not low NA system anymore. For example, ten years ago high image quality system usually had NA about 0.5-0.6 and NA of the Relays was 0.12-0.15. In decade NA of the Relay increased dramatically. Aberration such as spherical, coma and astigmatism strongly depends on degree of NA. Blur spot size depends on those aberration. Keeping blur spot size on the same level is a difficult task. For advanced lithographic tool the size of spot needs to be even smaller. This requirement increases the complexity of the Relay system. To simplify Relay design and analysis in these demanding conditions, authors suggest dividing a relay into two sub modules [3]: transform lens (TRL) and reverse transform lens (RTRL). This situation is shown on figure 4, and can be described by a mnemonic formula

$$\mathbf{R = RTRL+TRL} \quad \mathbf{(8)}$$

Formulae (8) demonstrates that relay consist of two independent sub-modules. If relay magnification equal 1X sub-modules are identical. 1X relay magnification is preferable also from aberration point of view because in this case relay is free from coma and distortion due to the symmetry of the arrangement. Besides field aberrations, pupil spherical aberration of the relay systems should be also corrected. Uncorrected pupil spherical aberration causes image field macro non-uniformity and pupil ellipticity. It is a consequence of positive vignetting.

5. Étendue modifiers.

In order to avoid light losses, the geometric étendue conservation law (generalized Lagrange invariant [7]) should be satisfied for optical path segments (subsystems) consisting of sequential optics [2]. Geometric étendue (geometric extent), **É**, characterizes the ability of an optical system to accept light. It is a function of the area **A** and the solid angle **Ω** into which it propagates. Étendue therefore, is a limiting function of system throughput[7]t:

$$\acute{E} \approx n^{2\cdot ¿ A\cdot\Omega} ¿ \, , \qquad \textit{(9)}$$

Where **φ** is measured relative the normal of the plane, and **n** is a refractive index of the medium. Being a constant for an optical segment with sequential optics étendue is determined by the least optimized element of that segment.

Laser sources used for illumination in lithographic systems tend to have very small étendue. As a consequence, it is very difficult to design laser light based illuminator with good uniformity over large area exposure fields and controlled divergence necessary to provide desired illumination mode in terms of partial coherence or pupil fill. To solve this problem multi-aperture and/or diffractive optical elements are employed as homogenizers. A typical multi-aperture optical element consists of lenslet arrays as shown in Figure 5 left. The first array and the condenser lens work as an afocal system. This arrangement is used as exposure field homogenizer. Figure 5 rights below illustrate illumination field homogenizer based on a diffractive array. In this case, every point on diffractive array acts as point source located at the font focal plane of a condenser.

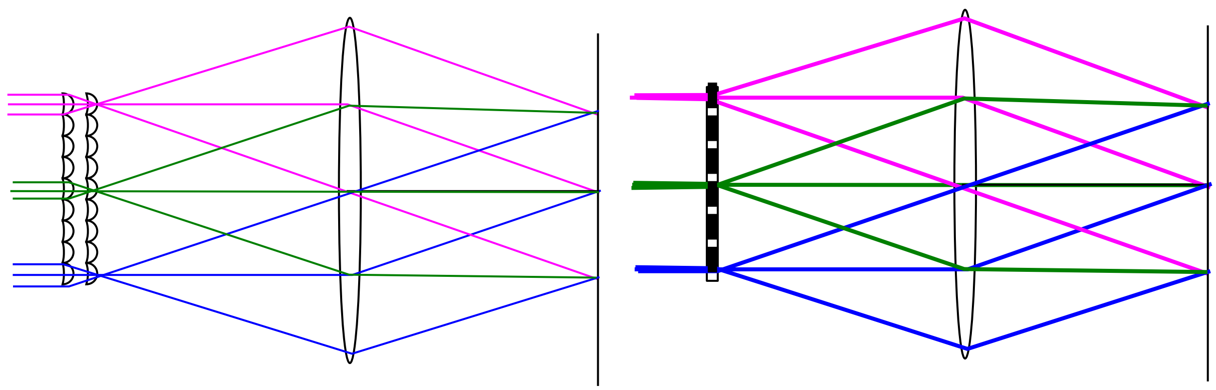

Figure 5.

Étendue modifier as illumination field homogenizer.
Left- multi-lens array; right – diffractive array.

6. Symbolic description of optical system

A symbolic description of an optical system can be offered using Fourier transforming properties of a lens 4] and Van Cittert - Zernike theorem5]]. For coherent illumination the fields in front of the lens and in the focal plane are related as two-dimensional Fourier transfor[8[4], and with an incoherent illumination the two-dimensional Fourier transform is applied to intensities distributio [9[5]. The generalized Van Cittert - Zernike theorem incorporates both resultsing introducing a coherence factor at the source. For the further analysis a table of symbolic operators is presented below

Table 2. Multiple Fourier Transform F^{A} and Related Operations

Multiple Fourier Transforms $\boldsymbol{F}^{A}$		
Multiplicity factor *A*	**Operator Symbol**	**Effective Operation Name**
0	$F^{0} = I$	Identity operator
1	$F^{1} = F$	Fourier operator
2	$F(F) = F^{2} = R$	Reflection operator
3	$F(F^{2}) = F^{3} = F^{-1}$	Inverse Fourier operator
4	$F(F^{3}) = F^{4} = I$	Identity operator
Other Operations		
	$\otimes$	Convolution
	$\times$	Function Product or Filter (point-by-point)

PDE is a diffractive and/or multi-aperture element modifying the étendue of the incident beam, so result is a convolution of angular structure of the source S with PDE.
Using symbols shown in Table 2 we can describe the system schematically presented in Fgure1.

after pupil defining element (PDE)	$S \otimes PDE \rightarrow$
after condenser lens C1	$F(S \otimes PDE) \Rightarrow F(S) \times F(PDE) \rightarrow$
after field defining element (FDE)	$[F(S) \times F(PDE)] \otimes FDE \rightarrow$
after condenser lens C2 at the delimiter	$(S^{R} \otimes PDE^{R}) \times F(FDE) \rightarrow$
after first lens of relay at the aperture stop	$F^{-1}(S \otimes PDE) \otimes FDE^{R} \rightarrow$
after second lens of relay at the reticle plane	$(S \otimes PDE) \times F^{-1}(FDE)$

The last equation tells us that the uniformity of illumination field at the reticle plane is formed by inverse Fourier transform of FDE function. The convolution of source and PDE functions is responsible for pupil fill or partial coherence of illumination.

7. Conclusion

Important issues of illuminators for high image quality tools are discussed. The illuminator design approach based on modularity of the optical components is proposed. Illuminator optical modules such as relays and condensers (or transform lens) can be divided on optical components. Each component realizes Kohler type of illumination. In this case each component can be designed and analyzed independently. Then components placed in proper order.
In this contribution we showed that Relays realizing Critical type of illumination can be represented by two transform lenses or condensers, one of them should be flipped.
This approach gives freedom use the similar type of optical components in different illumination systems.
We also discussed complexity of the different illumination modules and its dependence on optical characteristics such as aberration, vigneting, telecentricity error and packaging conditions. Role of the Étendue modifiers was explained.

8. REFERENCES

[1] M. Born and E. Wolf, "Principles of optics" 1980.

[2] L. Ryzhikov and Y. Vladimirsky, System and method utilizing a lithography tool having modular illumination, pattern generator, and projection optics portions; US Patent 7,242,456 (2007)

[3] L. Ryzhikov, et al, Relay lens used in an illumination system of a lithography system, EU patent 1,380,871, 2006

[4] L. Ryzhikov, Y. Vladimirsky, LIS design for optimum efficiency, SPIE Proceeding, 6154, 2006

[5]A.E. Conrady, "Applied Optics and Optical Design" 1957 part 1, page 448

[6]G.G. Slusarev, "Geometrical optics" 1946, page 106

*[7] **Handbook of Optics**, Volume I, Second Edition (ed. M. Bass, McGRAW-HILL, 1995) page 1.25*

*[8] **J.W. Goodman, "**Introduction to Fourier Optics**"** 1996*

*[9] **J.W. Goodman, "**Statistical Optics**" 1985***