Catadioptric Projection Lenses for Immersion Lithography

Heiko Feldmann[*], Aurelian Dodoc, Alexander Epple, Hans-Jürgen Rostalski, David Shafer[†],
Wilhelm Ulrich
Carl Zeiss SMT AG, Carl-Zeiss-Strasse 22, 73447 Oberkochen, Germany
[†] David Shafer Optical Design, 56 Drake Lane, Fairfield, Connecticut, 06824

ABSTRACT

Recently, the development of high NA lenses for immersion lithography turned from dioptric concepts to catadioptric design forms. The introduction of mirrors involves the new challenge to deal with the inevitable obscuration of either field or pupil. We review the strategies used in this regard for microlithography, while focussing on the two most favored ones, folded and inline concepts. Although the vignetting situation is more complicated for inline systems, we report progress in this field of optical design yielding similar system performance for inline and folded designs. Since inline optical systems are much easier to realize, these are the concept of choice.

Keywords: Immersion lithography, High NA, Catadioptric designs

1. INTRODUCTION

Mirrors as a design means for lithographic lenses have a tradition of several decades. The first reason for their attractiveness was the simple unit magnification systems based on the concepts of Dyson and Offner [1]. Later reduction systems were required for lithography. Although some steps have been taken to implement reduction systems on a catadioptric basis [2], dioptric lenses started to dominate the development. For projection optics with i-line (365nm) lamps as light sources, several kinds of optical glass could be used for achromatization, and mirrors were not used for leading edge lithography.

However, the industry demands to continuously shrink the dimensions of the electronic circuits structured by lithographic projection. This increasing request drives the trend to use smaller wavelengths and higher numerical apertures.

After a long period dominated by dioptric reduction systems, mirrors were again discussed and used to enable color correction for 157nm lithography, where no second optical material is available and laser bandwidths can not be sufficiently narrowed. Also, early 193nm systems for broad-band lasers were based on catadioptric designs [3].

With the advent of immersion, the circumstances changed again. The maximum NA now was extended far beyond 1.0, and the wavelength of 193nm can be used for the small features that previously seemed to require the wavelength of 157nm (or even EUV). At this wavelength, dioptric systems that are made almost exclusively from fused silica have already demonstrated that full color correction is not imperative for the technology to work, although it may be economically advantageous to allow broader wavelength lasers.

As a second benefit of mirrors, the textbooks on optical design mention their contribution to field curvature, which is inverse to the contribution of refractive lenses. This objective to control field curvature can also be achieved with a dioptric design using small negative and large positive lenses. However, during the first studies on extreme high NA immersion designs, it became clear that this dioptric concept leads to extremely large designs beyond approximately NA=1.1, using an extreme amount of optical material. So the most important motivation to look for catadioptric systems now is to find another way to satisfy the Petzval condition and in this way to obtain a compact system at reasonable costs.

---

[*] Correspondence: email h.feldmann@smt.zeiss.com; phone +49 (0)7364 20 8388; fax +49 (0)7364 20 2334

Optical Design and Engineering II, edited by Laurent Mazuray, Rolf Wartmann
Proc. of SPIE Vol. 5962, 59620Y, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.625199

In contrast to other design means like e.g. aspheres [4] or diffractive elements [5], mirrors can not be introduced smoothly into a design concept: they immediately pose the problem of separating the incident and the reflected beam. This new condition determines the basic layout of the system. It is a goal of this paper to give a coherent picture of catadioptric concepts, based on the principles invoked to handle the beam separation issue.

2. SEVERAL WAYS TO REACH BEAM SEPARATION

Probably the most frequently used strategy is to use an obscured pupil, where some small part of the optics is in front of a large pupil mirror. Sometimes a hole allows the image to pass through this large mirror if object and image have to be on opposite sides of the lens. For microlithography, such an obscured pupil would render the imaging difficult, and is therefore not wanted. For the rest of the paper, we discuss solutions with complete pupils.

The optical designer can also try to ignore the problem of beam separation and pass it on to physics: a beamsplitter may be used to separate the beams. Of course, the optical design has to provide enough volume for the beamsplitter, but this can easily be achieved. This concept has already been studied for lithography. Two design examples are shown in Fig. 1.

.

One variant is to split the energy of the rays, but the energy loss of 75% is not acceptable for most applications. Another way is to use polarizing layers to separate the rays, using quarter wave plates to properly manipulate the polarization. In the latter case, the intensity loss of the system is not as severe, but only one polarization state can be used for imaging. A discussion of the properties of a beam-splitter coating is e.g. given by ref. [6].

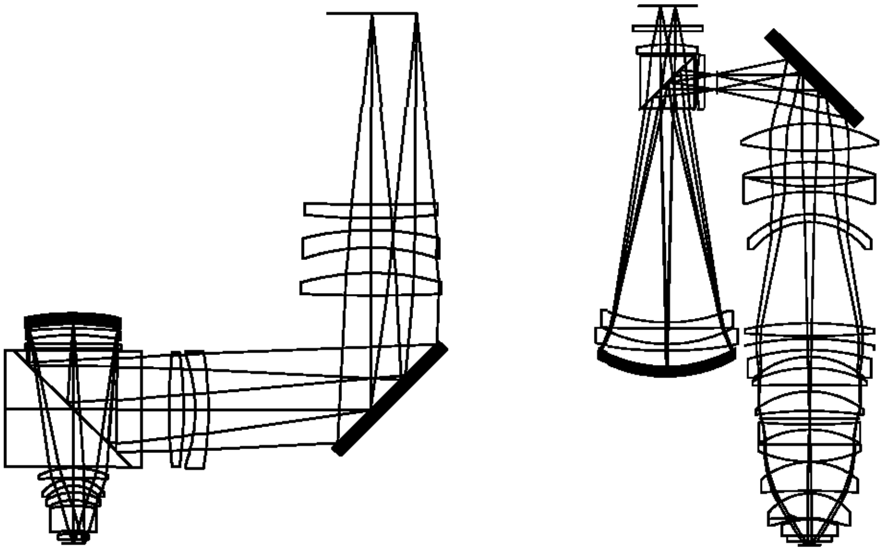

Fig. 1: Lithography lenses designed around beam splitting cubes
Left: a large cube close to the aperture stop [7]
Right: a design minimizing the size of the beam splitter cube [8]

If the beam splitting element is close to a field conjugated plane, the system may be transformed to the second class of solutions: a system with off axis field, where the beam separation is facilitated by folding mirrors. The shifted image field now leads to a higher etendue and thus to more effort to correct the design, but the folding mirror is usually simpler to produce than a beamsplitter, and the system has the theoretical ability to image with less influence on polarization. In this sense, the folded design in Fig. 3 (Left) has been developed on the basis of Fig. 1 (Right).

Working on different configurations for a folded design, a simple design strategy emerges: although it is clear that the used field of a folded design can not include the optical axis, the designer can try to keep the off-axis field as central as possible. The total etendue to be corrected is kept as small as possible. At the folding position, ideally there are two planes conjugated to the field on opposite sides of the optical axis, as shown in Fig. 2. In reality, we have to deviate from this ideal situation, because we do not want to have an optical surface (folding mirror) directly in a field plane. Also, the intermediate image is usually not well corrected in order to allow aberrations to cancel between different subsystems.

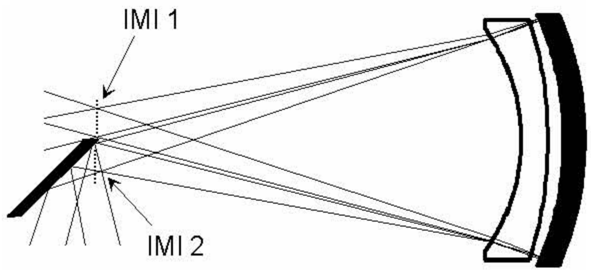

Fig. 2: Ideal arrangement for folding systems: Two field planes (IMI: object, image, or some intermediate image) adjacent to the folding position.

When the NA increased further for immersion lithography, the beam separation became a more and more difficult issue. The recipe to move the folding mirrors as close as possible to a field plane seemed to be exhausted. Now the development took an interesting twist: A new complete relay system was added to the designs just to follow this recipe even more rigorously. Surprisingly, the system gain from this step greatly outbalanced the additional effort. Today, these folded catadioptric lithography designs reach numerical apertures higher than NA 1.2 within the same volume that previous concepts used around NA 0.9.

A second surprise was the attempt to add again one subsystem, this time a new catadioptric system on the yet unoccupied side of the central folding region. With the second mirror, a better control over color, field curvature and higher aberrations rendered the total system approximately as advantageous in terms of dimensions and weight as the one mirror version. All these approaches are illustrated in Fig. 3.

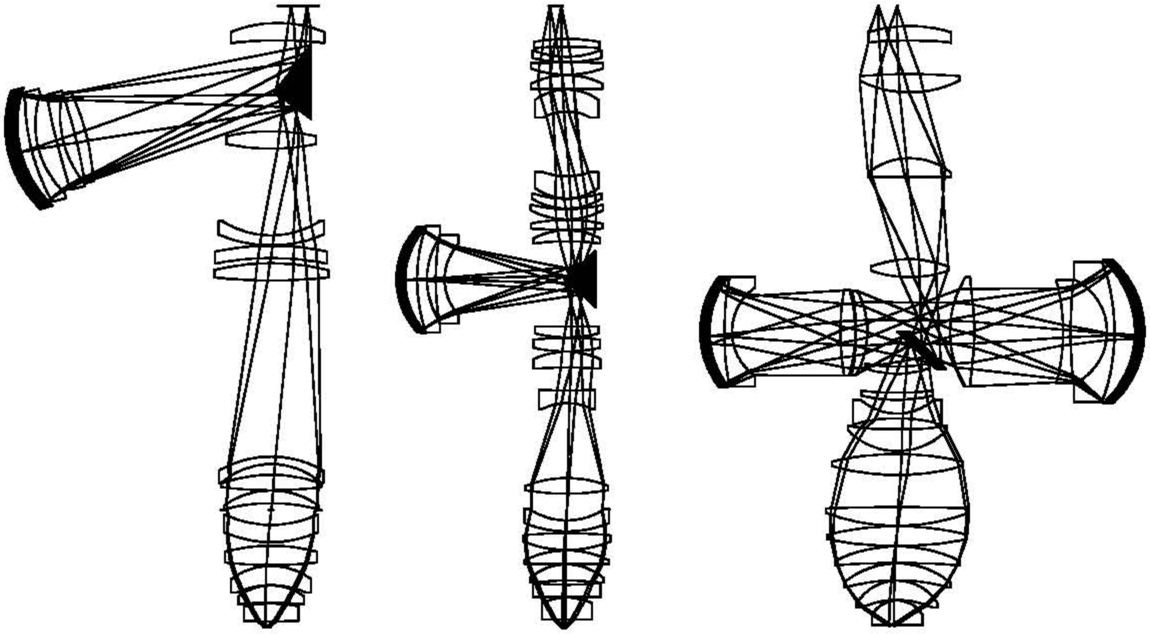

Fig. 3:
Left: "Traditional" folded design with one intermediate image [9]
Center: A whole new relay system is added to ease the folding (2 intermediate images) [10]
Right: Even the addition of a second catadioptric group can be beneficial for the total system (3 intermediate images) [11]

From a theoretical point of view, these designs are very attractive: an easy to understand rule "fold close to the intermediate images" deals with the issue of beam separation and the designer can concentrate on his main task to find an optimum balance of aberrations.

The practical realization of the systems in this section, however, meets some obstacles. For example, additional effort is required to manufacture an optical system with more than one optical axis. A part of this effort is shown in [12]. In addition, the tilted folding mirrors have high incidence angles. These reflections lead to a degradation of the polarization behavior, which breaks the rotational symmetry of the system. Also, most of the folded systems have an odd number of mirrors and thus flip the image. Then they are not compatible with reticles for traditional dioptric lenses.

For these reasons we should not be satisfied with the results so far and see if we can find configurations without folding mirrors. We may be encouraged by the experience that for catadioptric microlithography lenses, a seemingly higher effort is sometimes the better solution.

3. THE CLASS OF INLINE SYSTEMS

3.1 An early inline system

A rotationally symmetric optical system without folding elements has one common axis of rotational symmetry for all optical elements. We call these "inline systems".

Catadioptric inline systems have been studied for a long time. One of the earliest designs for lithography is shown in Fig. 4. We can use it to discuss issues and strategies to deal with clearance control for inline systems. The design consists of two subsystems, the first one is catadioptric and the second one is only refractive. In the catadioptric relay system, the first mirror reflecting the light is close to the pupil plane, and is close to a negative power refractive lens element, making up a Schupmann achromat. The second mirror, reflecting the light again in the direction of the image, is situated between pupil and intermediate image, so that the footprint of the off axis field is decentered at this mirror. This allows to cut the second mirror, letting the rays pass it without obscuration of the pupil. The intermediate image has approximately the same size as the object, but it features an overcorrected field curvature and overcorrected axial color. The main task of the second subsystem is then to provide the high numerical aperture on the final image side, where for lithographic applications the wafer is located. A large collection of extensions of this principle based on the Schupmann achromat can be found in [13].

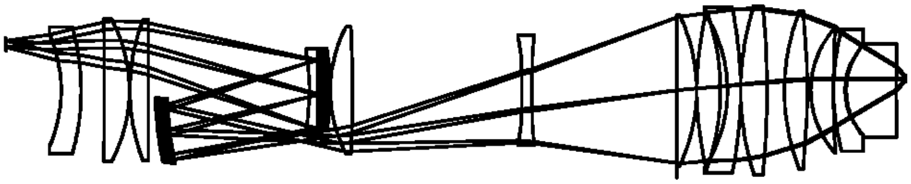

Fig. 4: One of the earliest catadioptric inline designs [14]

While the design in Fig. 4 exhibits all the ingredients we want for an inline catadioptric projection system, there are still open issues: the usable section of the field height is relatively small, and we would have to scale up the design by a large factor to obtain an image field of sufficient size. The standard field width of a lithographic scanner field is 26 mm on the image side, and rectangular fields are preferred over arc shaped fields (see [15] for a discussion of ring field).

Lithographic projection lenses already have dimensions of more than about one meter length, and they have a large contribution to the total cost of the microlithographic steppers. Therefore scaling up the systems is prohibited, and other means to allow larger image fields are required. This challenge to control the vignetting becomes even more difficult when the aperture is increased.

Therefore we studied systematically the different possibilities to construct modified inline systems where better ways of beam separation allow a larger field size without increased system length.

3.2 Try to separate the beams at intermediate images

First, also here we can try to use the rule “separate the beams directly at intermediate images”.

Such an attempt is shown on the left side of Fig. 5. We put one intermediate image (IMI 2) directly onto a mirror (M2), construct the rest of the optical system in such a way that another intermediate image (IMI 1) is nearby, on the other side of the optical axis. Symmetry considerations suggest that the opposite mirror (M1) then is close to a system pupil or a congjugated plane. Now a severe problem is encountered: how can we get the rays past this pupil mirror? Since the pupil mirror is necessarily centered about the optical axis, the only way is to position the whole outline of the passing by beam off axis, close to another intermediate image. The only free variable we have for this purpose is the curvature of the second mirror, the one close to the second intermediate image. But since this mirror is at a field conjugated position itself, it only acts on the pupil position and can not help to create another intermediate image.

Optical design consists of balance and compromise. Still, we can try to optimize the position of the intermediate images to put them as close as possible to the mirrors as shown in Fig. 5 (Right). Now, both mirrors are in between a pupil and a field plane, and the usable range of field heights is already strongly increased with respect to the original inline design in Fig. 4.

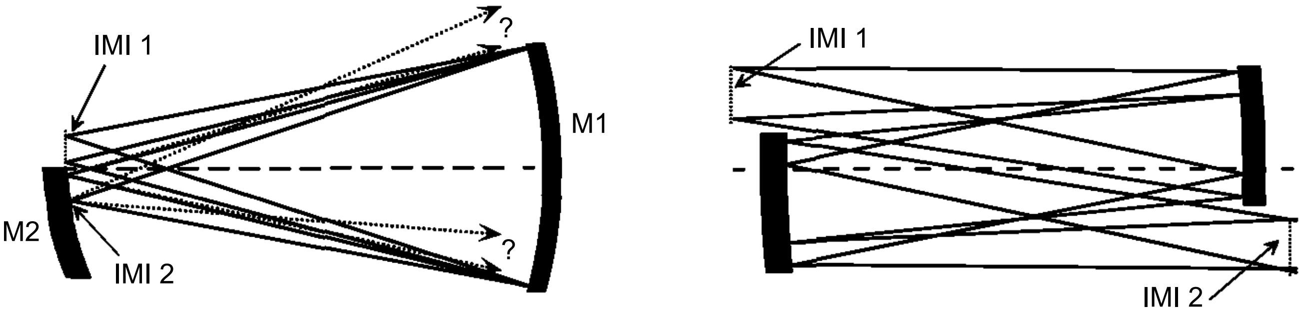

Fig. 5:
Left: The method of adjacent field planes works well for one mirror, but not for the opposite mirror.
Right: A compromise to apply the adjacent image construction for both mirrors.

In doing so, we have to give up the pupil mirror, where it was easy to implement color correction as in the Schupmann achromat. A contribution to axial color away from the system pupil inevitably introduces lateral color. This slightly complicates the situation. A solution is the use of (at least) two Schupmann constructions positioned on two sides of the system pupil. Then their contributions to the lateral color can be balanced. The detailed attempts to introduce these two color correcting mirrors have brought up a new system: by adding a new catadioptric relay system, the four mirrors allow several combinations of color correcting means. An example of this discovery is shown in Fig. 6 (Top). Again, the additional effort to add a complete new relay system is outweighted by the gain in system effort, measured e.g. in mass or volume.

The additional relay system may also be designed as a purely dioptric one, as illustrated at the bottom of Fig. 6. Here, however, the two mirrors have to bear the whole contribution of field curvature for the two refractive subsystems.

The lesson that was surprising to us was again: the introduction of additional intermediate images, which enhances the system complexity at the first glance, does not increase volume or weight of the lens. In some cases, the results even surpass the “simpler” designs.

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**