

Saddle-point construction in the design of lithographic objectives, part 1: method

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Abstract. The multidimensional merit function space of complex optical systems contains a large number of local minima. We illustrate a method to find new local minima by constructing saddle points, with examples of deep and extreme UV objectives. The central idea of the method is that, at certain positions in a system with N surfaces that is a local minimum, a thin meniscus lens or two mirror surfaces can be introduced to construct a system with $N+2$ surfaces that is a saddle point. When optimization rolls down on the two sides of the saddle point, two minima are obtained. Often one of these two minima can also be reached from several other saddle points constructed in the same way. With saddle-point construction we can obtain new design shapes from existing ones in a simple, efficient, and systematic manner that is suitable for complex designs such as those for lithographic objectives. © 2008 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2981512]

Subject terms: saddle point; lithography; optimization; optical system design; EUV; DUV.

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1 Introduction

In optical system design, the multidimensional merit function (MF) space typically comprises a large number of local minima. It has been shown recently¹⁻⁴ that these local minima are connected together via optimization paths that start from a specific type of saddle point (saddle point with Morse index 1) and form a network. For complex systems the detection of the entire network is difficult and time-consuming.⁵ When the complexity is large, the generation of new local minima must be performed with methods that use a limited number of local optimizations to achieve their goal. An efficient and fast method to find new minima by constructing saddle points has been recently developed.⁶ This method is illustrated in the present study with examples of objectives for deep and extreme UV lithography. The present study consists of two parts: In this article we focus on how the method should be applied in lithography, and in an accompanying article we will show that this method can lead to high-quality designs.

A point in an N -dimensional MF space for which the gradient of the MF vanishes is called a *critical* point. An important characteristic of a critical point is the so-called Morse index (MI), which gives the number of mutually orthogonal directions along which the critical point is a maximum.¹ For example, two-dimensional saddle points always have $MI=1$, because they are maxima in one direction and minima along a perpendicular direction, a feature that gives them the familiar horse-saddle shape. Special cases of critical points are maxima (MF decreases in all directions, $MI=N$) and minima (MF increases in all direc-

tions, $MI=0$). Critical points with $MI=k$, $0 < k < N$, are saddle points that are maxima in k directions and minima in $N-k$ directions. (At critical points for which the Hessian matrix of the second-order derivatives of the MF with respect to the optimization variables has a nonzero determinant, MI is defined as the number of negative eigenvalues of the Hessian. The directions mentioned are those of the eigenvectors of the Hessian. A negative [positive] eigenvalue means that along the corresponding eigenvector the critical point is a maximum [minimum].)

For our purpose, it is sufficient to consider saddle points with $MI=1$. Despite the fact that the dimensionality is arbitrary, their fundamental property can be easily grasped. Saddle points with $MI=1$ are just a straightforward generalization of two-dimensional saddle points: the MF decreases on two sides along the unique maximum direction, and increases in any other direction orthogonal to that direction.

From such a saddle point, two distinct local minima can be generated by letting the optimization go down on its two sides. The optimization paths, together with the saddle point with $MI=1$, form a link in the optimization space between the two minima.

The analysis of the MF landscape for simple systems has revealed properties that enable the efficient generation of local minima by a technique called saddle-point construction that is valid for systems having arbitrary complexity. It turns out that from a given local minimum with N surfaces we can construct saddle points with $MI=1$ having $N+2$ surfaces by inserting at any surface in the local minimum a zero-thickness meniscus lens (or two mirror surfaces with zero distance between them).^{6,7} Any optical MF can be

used, e.g., a MF based on transverse aberrations (root-mean-square spot size), wavefront aberration, etc.

A very powerful version of the saddle-point construction method is the one in the special case when the zero-thickness meniscus is inserted in contact with (i.e., at zero axial distance from) an existing surface (called the reference surface) at the original local minimum, and when the glass of the new lens is the same as the one at the reference surface. Below we summarize the method in the special case; full details can be found in Ref. 6. In the general case, when the insertion position and the glass of the new lens are arbitrary, the curvature of the meniscus can be computed numerically.⁷

In the initial system, we denote the curvature of the k 'th surface (the reference surface) by c_{ref} , and the MF by MF_{ref} . After this surface we insert a thin lens with the two curvatures c_{k+1} and c_{k+2} that has zero axial thicknesses both for the lens and for the airspace between the thin lens and the reference surface where it was introduced. The initial value of the MF, MF_{ref} , remains unchanged (because all rays pass undeviated) when:

1. the two curvatures c_{k+1} and c_{k+2} , are equal (thin meniscus);
2. the two curvatures c_k and c_{k+1} are equal, and c_{k+2} is equal to the curvature of the reference surface, c_{ref} (thin air meniscus before the new lens).

The transformations

$$c_k = c_{\text{ref}}, \quad c_{k+1} = c_{k+2} = u, \quad (1)$$

$$c_k = c_{k+1} = v, \quad c_{k+2} = c_{\text{ref}} \quad (2)$$

(all other variables are kept unchanged) describe two lines in the variable space of the new system with $N+2$ surfaces (in Fig. 1 these two lines are shown symbolically in the plane defined by them). As already shown, along both lines the MF is invariant and equal to MF_{ref} . The two invariant lines intersect at $u=v=c_{\text{ref}}$, i.e.,

$$c_k = c_{k+1} = c_{k+2} = c_{\text{ref}}. \quad (3)$$

It can be shown that in this case the system is a saddle point.⁶

In the preceding analysis, a thin lens with surfaces $k+1$ and $k+2$ is inserted after the k 'th surface in an existing design that is a local minimum. However, Eqs. (1)–(3) are also valid if a thin lens with surfaces k and $k+1$ is placed before the $k+2$ 'th surface in an existing minimum.

The position of individual points along these lines is given by the parameters u and v . For example, two points can be defined on each line [p_{1-} , p_{1+} on the line (1), and p_{2-} , p_{2+} on the line (2)] by setting in Eqs. (1) and (2), e.g.,

$$u = (|c_{\text{ref}}| \mp \varepsilon) \cdot (-1)^n, \quad (4)$$

$$v = (|c_{\text{ref}}| \mp \varepsilon) \cdot (-1)^n, \quad (5)$$

where

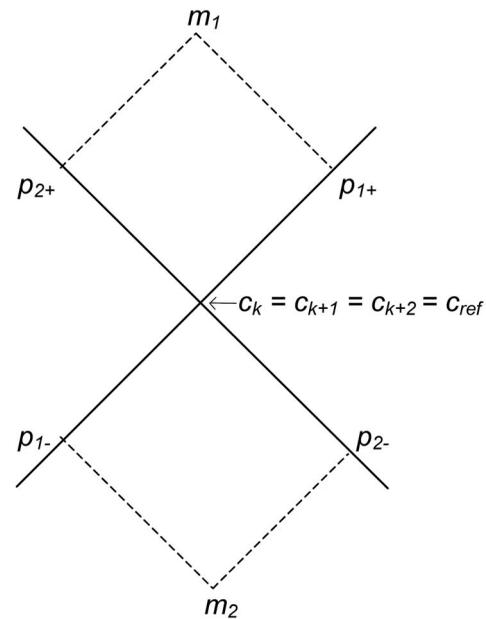


Fig. 1 Lines in the MF subspace defined by three of the curvatures of the new system with $N+2$ variables. The dashed lines indicate symbolically which local minimum is obtained by locally optimizing the corresponding point on the continuous line, assuming that the initial system is well optimized, i.e., that the gradient of the MF is close enough to zero.

$$n = \begin{cases} 0 & \text{if } c_{\text{ref}} > 0, \\ 1 & \text{if } c_{\text{ref}} < 0, \end{cases}$$

ε indicates a small change in the curvature, and the sign in front of ε is the one appearing in the subscript of the corresponding point.⁸ When local optimization is performed at these points, two new local minima (with $N+2$ surfaces) are generated, m_1 and m_2 . Finally, at each minimum the thickness of the inserted thin meniscus and the distance between it and the reference surface where it was introduced are increased. (At the resulting minima, the glass type of the new lens can also be changed if desired.)

In practical applications, it is in general sufficient to use only one pair of points, given either by Eq. (4) or by Eq. (5). The entire process of constructing saddle points is illustrated in Fig. 2.

The method can be used when all curvatures are variables, as well as when some of them are kept constant to play the role of control parameters. The systems studied in this article are lithographic objectives.^{8–14} The method is here applied to monochromatic objectives, in which all lenses are made of the same material.

In the next section we describe a special type of local minimum and its relationship with the saddle points constructed with our method. In Sec. 3 we discuss how the method presented in the flow chart can be used for generating mirror systems for extreme UV (EUV) lithography. Finally, we generalize the method for optical systems with aspherical surfaces.

2 Hubs for Deep UV Lithographic Objectives

We have shown earlier that local minima form a connected network in the MF space.^{1–4} For simple optical systems it has been observed that some minima have a large number

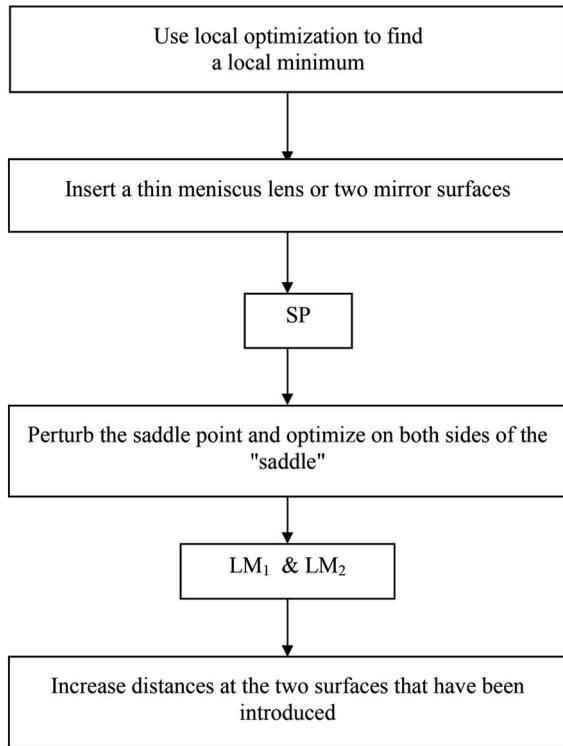


Fig. 2 Flow chart for the saddle-point (SP) construction method for obtaining two new local minima LM₁ and LM₂.

of links in the network (the *hubs*).³ The hub property is interesting because it seems to be associated with a relaxed design (i.e., a design that is insensitive to small changes of one or more parameters). In this section we show that hubs exist for deep UV (DUV) lithographic objectives as well.

Figure 3 shows a lithographic objective having 43 surfaces (including the stop) that is closely related to the system described in Refs. 15 and 16. The numerical aperture is 0.56, the image height is 11 mm, the magnification is -0.25, and the wavelength is 248 nm. All surfaces are spherical, and all 42 surface curvatures have been used as variables in our research.

The saddle-point construction method is illustrated in detail for the second bulge. For studying the existence of the hubs in the MF space, all thicknesses of the lenses between surfaces 34 and 39 (see Fig. 3) have been made equal. The two small distances between the corresponding lenses have also been made equal. (As is shown below, this is necessary for obtaining the same system in different ways. For the practical purpose of generating new optical systems the lens thickness and the axial thickness of the air space between the lenses can be kept at the initial values.)

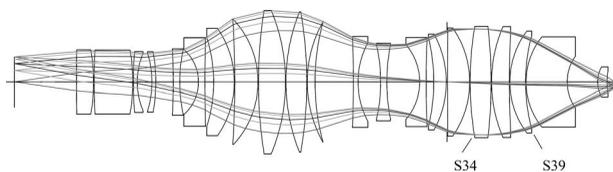


Fig. 3 Lithographic objective with $N=43$.

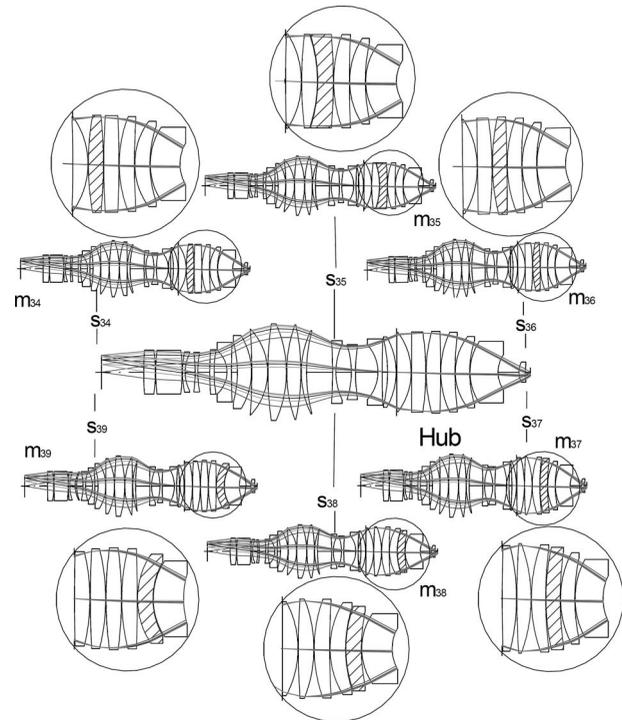


Fig. 4 Hub with six links in the network of local minima for a monochromatic lithographic objective with $N+2=45$ surfaces. For a better comparison, the parts of the drawing at those m_i where the most significant changes take place when inserting the meniscus are enlarged (encircled). The indices show the surface in the original system where an extra lens has been inserted, and the new lens resulting from the meniscus is shown hatched. Because of the zero distances and equal curvatures in the method, the lens drawings for the saddle-point systems, s_i , are indistinguishable from the drawings in Fig. 3.

Successively, at each surface in this group, a thin meniscus lens has been inserted as already described. [See Eq. (3).] In this way, we have constructed six saddle points with 45 surfaces (including the stop). From each saddle point, two points are selected as defined by Eq. (4) or (5), each situated on one side of the saddle point, and by means of local optimization performed at these points, two new minima have been generated. Interestingly, when the thickness of the thin meniscus is increased to the same value as that for the other lenses in the group S34 to S39, six of the twelve local minima become identical (the hub), and on one side all six saddle points that have been constructed are linked to it, as shown in Fig. 4. In this figure, the saddle points are denoted as s_i and the other six minima (shown after increasing the thickness of the meniscus) are denoted by m_i , where i indicates the surface where the meniscus has been inserted. We have observed that, in all cases, the hub has resulted from the local minima obtained from the saddle point using Eq. (5) $[v = (|c_{ref} - \epsilon) \cdot (-1)^n]$. If desired, the meniscus thickness can be increased at the saddle points s_i as well (these saddle points, not shown in detail in Fig. 4, continue to exist), but the method for doing this is more elaborate and for the purpose of generating local minima this is not necessary.

With the meniscus still thin, in the case of lithographic objectives, a minimum that will become a hub has always a higher MF value than the one on the other side of the

saddle point, but surprisingly, after adding thickness the trend is reversed. In the case shown in Fig. 4, the value of MF of the hub is between 0.1% and 63% lower than the MFs of the various m_i . For simplicity, in the rest of the article the local minima obtained after increasing the thickness of the thin meniscus in the solutions obtained from the saddle points are referred to as local minima generated from the saddle points.

Similar results have also been obtained at the first bulge. Interestingly, there we have generated two hubs, each connected to three saddle points. When, at the two hubs, additional constraints are used to control the minimum edge thickness between lenses (between surfaces 18 and 21), they merge into a single hub.

If the number of surfaces in the design must remain unchanged, one can extract a lens (with suitable intermediate steps) at some position in the hub. A strategy to extract lenses that was successful is the following. The thickness of the lens to be extracted and the distance between the lens and the preceding or following one are reduced in appropriate steps to zero. The surfaces of the new thin lens are then made equal to the surface with which they are in contact. At this stage, the obtained thin meniscus can be removed without affecting the system performance. For example, from the hub with 45 surfaces in Fig. 4, we have successively extracted a single lens between surfaces 34 and 41. In all cases, via local optimization we have obtained the same minimum with 43 surfaces, which is actually the starting system (Fig. 3).

In fact, the starting system is also a hub. To illustrate this property, from the (slightly modified) starting system (now with lenses having equal thicknesses in the second bulge) we have extracted a lens from the second bulge. A local minimum with 41 surfaces has been obtained. In the new minimum, we have successively inserted a meniscus lens at each surface between surfaces 34 and 38. The five constructed saddle points are linked on one side to minima, which, after adding thickness, again merge into a single hub, the starting system with 43 surfaces (see Fig. 5). As can be observed from Fig. 3, this system is a relaxed design. The fact that it is a hub supports the hypothesis that there is a correlation between the hub property and relaxation.

When inserting a meniscus lens in a system we observe that most changes in the configurations occur locally where the new lens has been introduced (see Fig. 4). The surface curvatures in the rest of the system tend to remain unchanged. For increasing computational efficiency, such surfaces can be fixed during the processes of constructing saddle points and generating local minima.

Runs with a number of variables reduced, for the reason mentioned, to 18 have also been performed. Interestingly, these variables are sufficient to place the local optimization in the basin of attraction of the hub. The remaining 26 surface curvatures, which are fixed during these runs, are, in fact, used only for polishing the final design.

3 Constructing Saddle Points in Extreme UV Projection Optics

The saddle-point construction method has also been used for ring-field mirror systems for EUV lithography to illustrate how configurations having new shapes can be gener-

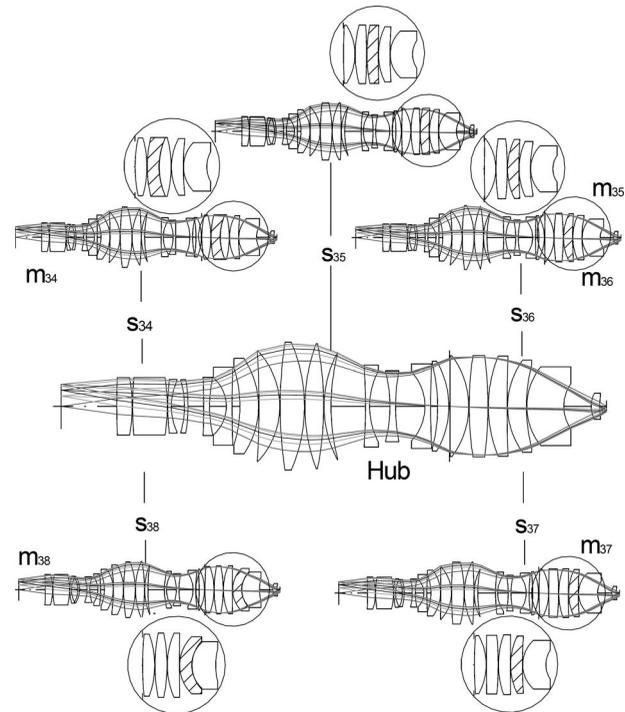


Fig. 5 Part of the network around the lithographic objective shown in Fig. 3, which is also a hub.

ated from the existing ones in a systematic way. In this section we show how six- and eight-mirror EUV systems can be generated when starting from a local minimum with four mirrors¹⁷ (see Fig. 6).

For simplicity, the four-mirror design selected as a starting point has all surfaces spherical (m_4 in Fig. 6). All four curvatures are variable. The numerical aperture is 0.16, the ring image height is 29.5 mm, and the magnification is 0.25. In this phase, the default CODE V¹⁸ MF, based on transverse aberration, has been used for optimization. Constraints have been used to control the telecentricity on the image side and the quasitelecentricity on the object side (i.e., the upper marginal ray must be parallel to the optical axis).

First, we have constructed two saddle points with six surfaces, $s_{6,2}$ and $s_{6,3}$ by inserting a pair of mirrors before the second surface (for obtaining $s_{6,2}$) and before the third surface (for obtaining $s_{6,3}$). The two mirrors have the same spherical shape as that of the surface where they have been introduced. The axial distances between the three consecutive mirrors are initially zero. From each saddle point, by means of local optimization, two new local minima are detected. On increasing the axial distances between the three consecutive mirrors and reoptimizing the configuration using as variables the surface curvatures and the object and the image distances, four solutions ($m_{6,S2A}$, $m_{6,S2B}$, $m_{6,S3A}$ and $m_{6,S3B}$), having different shapes, are obtained, as can be seen in Fig. 6.

For both saddle points one of the minima with zero distances detected from the saddle point has a much larger MF than the other one. Surprisingly, when we increase the axial distances between the mirrors, the situation is reversed and the poorer solution becomes the better one.

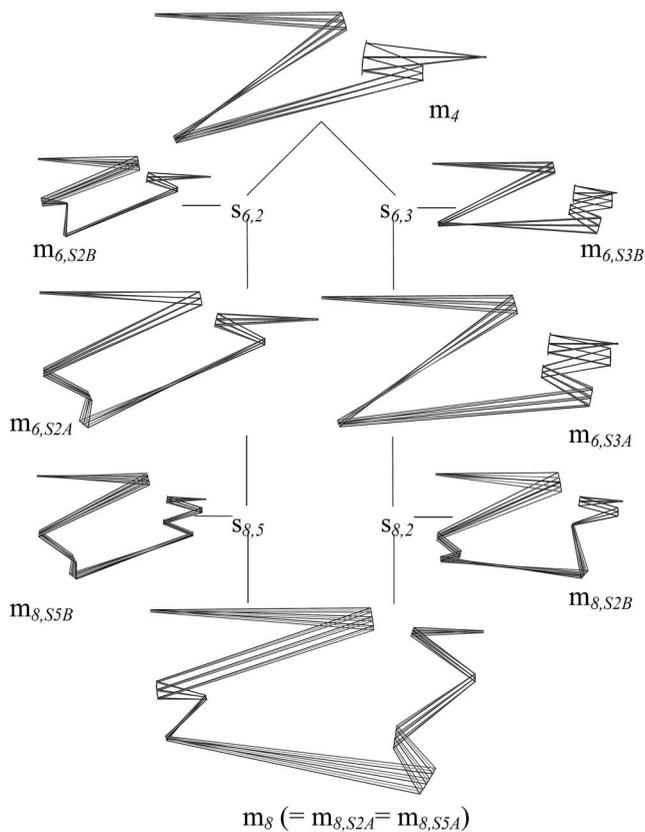


Fig. 6 Saddle-point construction method in extreme UV projection optics. The insertion of a pair of mirrors at different positions in a four-mirror system results in two saddle points, $s_{6,2}$ and $s_{6,3}$, with six surfaces. The process is repeated at the two local minima $m_{6,S2A}$ and $m_{6,S3A}$. The resulting two saddle points, $s_{8,2}$ and $s_{8,5}$, are connected to the same eight-mirror local minimum, m_8 . For the systems in the figure, the first subscript gives the number of mirrors, s indicates a saddle point, and the indices show the surface where the pair of mirrors has been inserted in the local minimum. Also, m indicates the local minima, and the subscript shows the saddle point from which they have been obtained. The minima with the better imaging performance are indicated with A.

Thus, we used the solutions $m_{6,S2A}$ and $m_{6,S3A}$, the ones with the better imaging performance detected from $s_{6,2}$, and $s_{6,3}$, respectively as starting points in the process of constructing new saddle points with $6+2=8$ mirrors. We inserted a pair of mirrors before the fifth surface in $m_{6,S2A}$, constructing the saddle point $s_{8,5}$ which has eight surfaces. From this saddle point, the two solutions $m_{8,S5A}$ and $m_{8,S5B}$ are detected. In the same way, by inserting the pair of mirrors before the second surface we detected two solutions having eight mirrors ($m_{8,S2A}$ and $m_{8,S2B}$) from $m_{6,S3A}$. Surprisingly, both saddle points $s_{8,2}$ and $s_{8,5}$ are connected on one side to the same solution. In fact, a further analysis shows that this solution, m_8 , is connected in the MF landscape to even more saddle points. Seven saddle points have been constructed by successively inserting the pair of mirrors as follows:

1. after the fourth surface and before and after the fifth and the sixth surface in $m_{6,S2A}$
2. after the first surface and before the second surface in $m_{6,S3A}$.

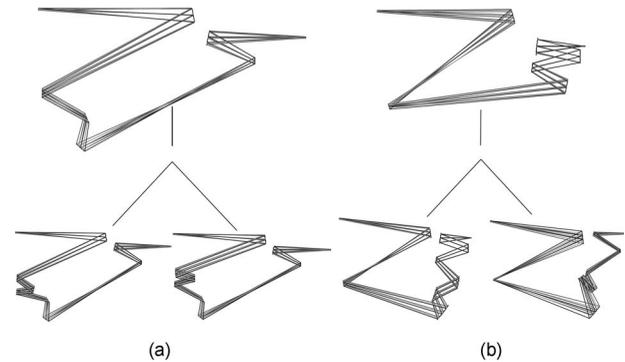


Fig. 7 Other eight-mirror systems, which have good imaging performance, obtained by constructing saddle points in six-mirror solutions in Fig. 6. A pair of mirrors has been inserted (a) before the second surface of $m_{6,S2A}$ and (b) before the third surface of $m_{6,S3A}$.

On one side, all these saddle points lead to m_8 . Similarly, the two solutions that have six mirrors, $m_{6,S2A}$ and $m_{6,S3A}$, are connected to at least three saddle points. Other design shapes can also be obtained. If in $m_{6,S2A}$ and $m_{6,S3A}$ saddle points are constructed at the second and the third surface, respectively, new solutions having eight mirrors are generated. For instance, the insertion of the pair of mirrors before the second surface in $m_{6,S2A}$ results in the two solutions illustrated in Fig. 7(a); if the pair of mirrors is inserted before the third mirror in $m_{6,S3A}$, the two solutions shown in Fig. 7(b) are obtained.

4 Generalization for Aspheric Surfaces

A generalized version of the saddle-point construction method for aspheric surfaces has been also applied in EUV design. At aspheric reference surfaces, saddle points are created by inserting a pair of mirrors with the same aspheric shape as that of the reference surface. As an example, a four-mirror system having aspherical surfaces, with aspheric coefficients going up to the 18'th order on each surface, has been used as the starting point¹⁷ (see Fig. 8). The default CODE V MF has been used for local optimization. During the process of constructing saddle points, extra constraints have been used to control the upper marginal ray leaving the mask and the chief ray leaving the last mirror to be parallel to the optical axis. A pair of mirrors has been inserted before the third surface. From the constructed saddle point $s_{6,3}$, two solutions having the shapes illustrated in Fig. 8 were obtained.

5 Conclusions

Recently, a method that uses saddle points in the design landscape has been proposed to generate efficiently new optical system configurations from known ones. The new method is applicable to the design of optical systems of arbitrary complexity, but is especially interesting for complex systems with a large number of variables, where computational efficiency becomes extremely important, and where other powerful tools, such as global optimization, cannot be easily applied. The method can be integrated easily with traditional design techniques and is, in fact, a useful alternative to the traditional way of inserting or splitting lenses in existing designs. Traditionally, inserting a lens in

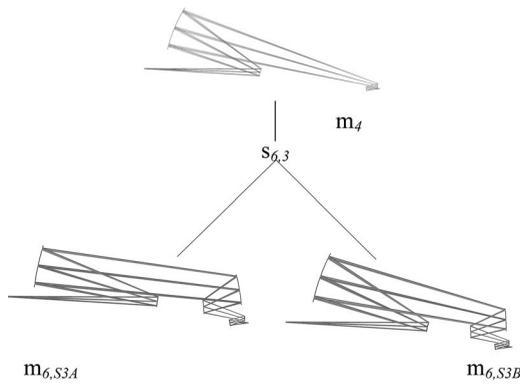


Fig. 8 Configurations with a numerical aperture of 0.15 and image height of 23.8 mm with 4+2=6 aspheric mirrors generated with saddle-point construction from m_4 .

an optical system always results in a single solution. When the insertion is performed so that a saddle point is created, two solutions are obtained after optimization. Systems having new shapes are detected, which otherwise, using the traditional way, might not have been found. In this article, the method has been illustrated with examples of deep and extreme UV lithographic objectives. The systems prescription can be found in Ref. 19.

Since we can choose between the two resulting minima, adding new components via saddle-point construction splits the design path. Surprisingly, the opposite of path splitting also occurs frequently: two or more different design paths may lead in a later design stage to the same solution. For instance, in the example illustrated in Fig. 4 the same DUV lithographic design is obtained in six different ways from the same system with less lenses. In the example in Fig. 6, the same eight-mirror EUV lithographic design (m_8) was obtained from two six-mirror systems ($m_{6,S2A}$ and $m_{6,S3A}$) having very different shapes. The fact that the same final design can be obtained in several different ways is important, because if for any reason a design route that should be successful accidentally misses the goal (e.g., for sufficiently complex systems, sometimes even the local optimization details influence the outcome of local optimization), in many cases the same goal can be achieved via another design route of the same kind.

The existence of a special type of local minima, the hubs, has been demonstrated for lithographic objectives. Such minima are connected to more saddle points than usual local minima. In this work a way to generate hubs is shown. A high-quality design for lithography at 248 nm is actually a hub.

We have applied the saddle-point construction method in several designs of DUV dioptric and catadioptric lithographic objectives, and of EUV objectives.²⁰ Examples of high-quality designs obtained with the new method will be given in the second part of the present study.²¹ In all these cases, the new method has significantly improved our design productivity.

Acknowledgment

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References

1. F. Bociort, E. van Driel, and A. Serebriakov, "Networks of local minima in optical system optimization," *Opt. Lett.* **29**(2), 189–191 (2004).
2. E. van Driel, F. Bociort, and A. Serebriakov, "Topography of the merit function landscape in optical system design," *Proc. SPIE* **5249**, 353–363 (2004).
3. F. Bociort, A. Serebriakov, and M. van Turnhout, "Saddle points in the merit function landscape of systems of thin lenses in contact," *Proc. SPIE* **5523**, 174–184 (2004).
4. F. Bociort, E. van Driel, and A. Serebriakov, "Network structure of the set of local minima in optical system optimization," *Proc. SPIE* **5174**, 26–34 (2003).
5. O. Marinescu and F. Bociort, "The network structure of the merit function space of EUV mirror systems," *Appl. Opt.* **46**, 8385–8393 (2007).
6. F. Bociort and M. van Turnhout, "Generating saddle points in the merit function landscape of optical systems," *Proc. SPIE*, **5962**, 0S1–8 (2005).
7. F. Bociort and M. van Turnhout, "Looking for order in the optical design landscape," *Proc. SPIE* **6288**, 628806 (2006).
8. O. E. Marinescu, "Novel design methods for high-quality lithographic objectives," PhD Thesis, Delft University of Technology, Sieca, (2006); available at <http://wwwoptica.tn.tudelft.nl/publications/Thesis/Marinescu.pdf>.
9. H. J. Levinson, *Principles of Lithography*, SPIE Press (2001).
10. S. Owa and H. Nagasaka, "Advantage and feasibility of immersion lithography," *J. Microlithogr., Microfabr., Microsyst.* **3**(1), 97–103 (2004).
11. J. J. M. Braat, "Extreme UV lithography, a candidate for next-generation lithography," *Proc. SPIE* **4016**, 2–7 (2000).
12. J. E. Bjorkholm, "EUV lithography—the successor to optical lithography?" *Intel Technol. J.* **Q3**, 1–8 (1998).
13. D. W. Sweeney, "Extreme ultraviolet lithography," in *Encyclopedia of Optical Engineering*, pp. 485–491, Marcel Dekker (2003).
14. H. J. Levinson and W. H. Arnold, "Opticle lithography," in *Handbook of Microlithography, Micromachining, and Microfabrication*, P. Rai-Choudhury, Ed., Vol. 1, pp. 11–126, Inst. of Engineering and Technology (1997).
15. T. Sasaya, K. Ushida, Y. Suenaga, and R. I. Mercado, "Projection optical system and projection exposure apparatus," U.S. Patent No. 5,805,344 (1998).
16. J. B. Caldwell, "All-fused silica 248-nm lithographic projection lens," *Opt. Photonics News* **9**(11), 40–41 (1998).
17. M. F. Bal, F. Bociort, and J. J. M. Braat, "Lithographic apparatus, device manufacturing method and device manufactured thereby," U.S. Patent No. 6,556,648 (2003).
18. Optical Research Associates, CODE V, Pasadena, CA.
19. <http://wwwoptica.tn.tudelft.nl/users/bociort/networks.html>.
20. O. Marinescu and F. Bociort, "Designing lithographic objectives by constructing saddle points," *Proc. SPIE* **6342**, 6342L1 (2006).
21. O. Marinescu and F. Bociort, "Saddle-point construction in the design of lithographic objectives, part 2: application," *Opt. Eng.* **47**(9), 093003 (2008) (this issue).



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