Saddle points in the merit function landscape of lithographic objectives

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ABSTRACT

The multidimensional merit function space of complex optical systems contains a large number of local minima that are connected via links that contain saddle points. In this work, we illustrate a method to construct such saddle points with examples of deep UV objectives and extreme UV mirror systems for lithography. The central idea of our 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 the optimization goes down on the two sides of the saddle point, two minima are obtained. We show that often one of these two minima can be reached from several other saddle points constructed in the same way. The practical advantage of saddle-point construction is that we can produce new designs from the existing ones in a simple, efficient and systematic manner.

Keywords: saddle point, lithography, optimization, optical system design, EUV

1. CONSTRUCTING SADDLE POINTS IN THE MERIT FUNCTION LANDSCAPE

In optical system design the multidimensional merit function space typically comprises a large number of local minima. It has been shown recently[1] that these local minima are connected via optimization paths that start from a specific type of saddle point (saddle point with Morse index of 1) and form a network. For complex systems the detection of the entire network is difficult and time consuming. In an accompanying paper in this volume, an efficient and fast method to construct saddle points with Morse index of one is described[2]. This method is illustrated in the present article with examples of lithographic objectives for deep and extreme UV.

A point in the merit function space for which the gradient of the merit function (MF) vanishes is called a critical point. At critical points, for which the Hessian matrix of the second-order derivatives of the MF with respect to the optimization variables has a non-zero determinant, the number of negative eigenvalues of the Hessian gives the so-called Morse index (MI). A negative eigenvalue means that along the corresponding eigenvector the critical point is a maximum and a positive eigenvalue means a minimum along the corresponding direction. Local minima have MI = 0, local maxima have MI = N and saddle points have MI between 1 and N-1. For the network structure it is sufficient to consider saddle points with MI = 1, i.e. saddle points that are maxima along one direction. From such a saddle point, two distinct local minima can be generated by letting the optimization go down on its two sides along that direction. The optimization paths, together with the saddle point with MI = 1, form a link in the optimization space between the two minima.

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 distances between them)[2]. (See Fig. 1.) In this paper, we apply this method to monochromatic lithographic objectives in which all lenses are made of the same material. In such cases, as shown in Ref. 2, if the thin meniscus is in contact (i.e. zero thickness) with the existing spherical surface, the shape of the thin meniscus is particularly simple. The curvatures of the

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two surfaces are identical with the curvature of the surface in the local minimum where the meniscus is introduced. Via local optimization performed on both sides of the saddle point, two new local minima (with N+2 surfaces) are then generated. Finally, at each minimum we increase the thickness of the inserted meniscus and the distance between it and the surface where it was introduced.

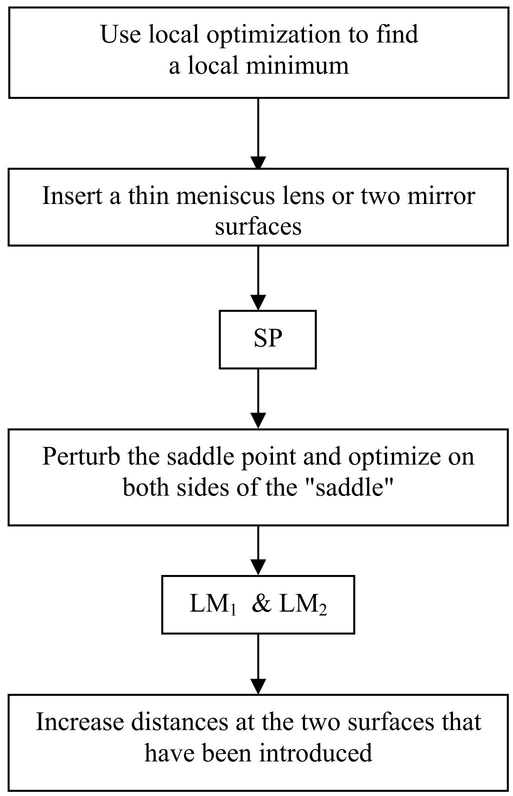

Fig. 1: Flow chart for the saddle point construction method.

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 practical purposes in the design of deep UV lithographic objectives. Finally, we discuss the method's applicability for extreme UV mirror systems.

2. HUBS FOR DEEP UV LITHOGRAPHIC OBJECTIVES

As shown in Ref. 2, some of the local minima in the networks for simple optical systems have a large number of links (the "hubs"). In this section we show that hubs exist for deep UV lithographic objectives as well.

Figure 2 shows a lithographic objective having 43 surfaces that is closely related to the system described in Refs. 3 and 4. 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 43 surface curvatures have been used as variables in our research.

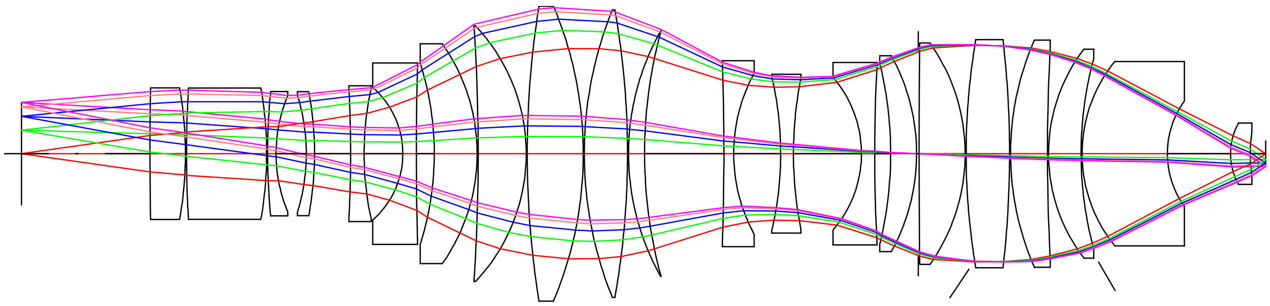

Fig. 2: Lithographic objective with N = 43.

First we insert the meniscus lenses in the second bulge. For illustrating more clearly the idea described below, all thicknesses of the lenses between surfaces thirty-four and thirty-nine (see Fig. 2) have been made equal. The two distances between these lenses have also been made equal and have a small value. Successively, at each surface in this group a thin meniscus lens has been inserted as described above. In this way, we have constructed six saddle points (MI =1) with 45 surfaces. From each saddle point, by means of local optimization performed on each side of the saddle, 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 S34-39, 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.3. In this figure, the other six minima (shown after increasing the thickness of the meniscus) are denoted by LM_i, where i indicates the surface where the meniscus has been inserted. If desired, the meniscus thickness can be increased in the corresponding saddle points SP_i as well (i.e. these saddle points, not shown in detail in Fig.3, continue to exist), but the method for doing this is more elaborate and for practical purposes this is not necessary.

With the meniscus still thin, a minimum which will become a hub has always a higher merit function 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. 3, the value of merit function of the hub is between 0.1% and 63% lower than the merit functions of LM_i. For simplicity, in the rest of the article the local minima obtained after introducing thickness to the thin meniscus in the solutions reached from the saddle points will be referred 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. For example, from the hub with 45 surfaces in Fig. 3, 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. Interestingly, this local minimum is actually the starting system.

In fact, the starting system is also a hub. To illustrate this property, from the starting system (with lenses having equal thicknesses in the second bulge) we have extracted one 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 s34 and s38. 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.

When inserting a meniscus lens in a system we observe (see Fig. 3) that most changes in the configurations occur locally, there where the new lens has been introduced. Most of 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.

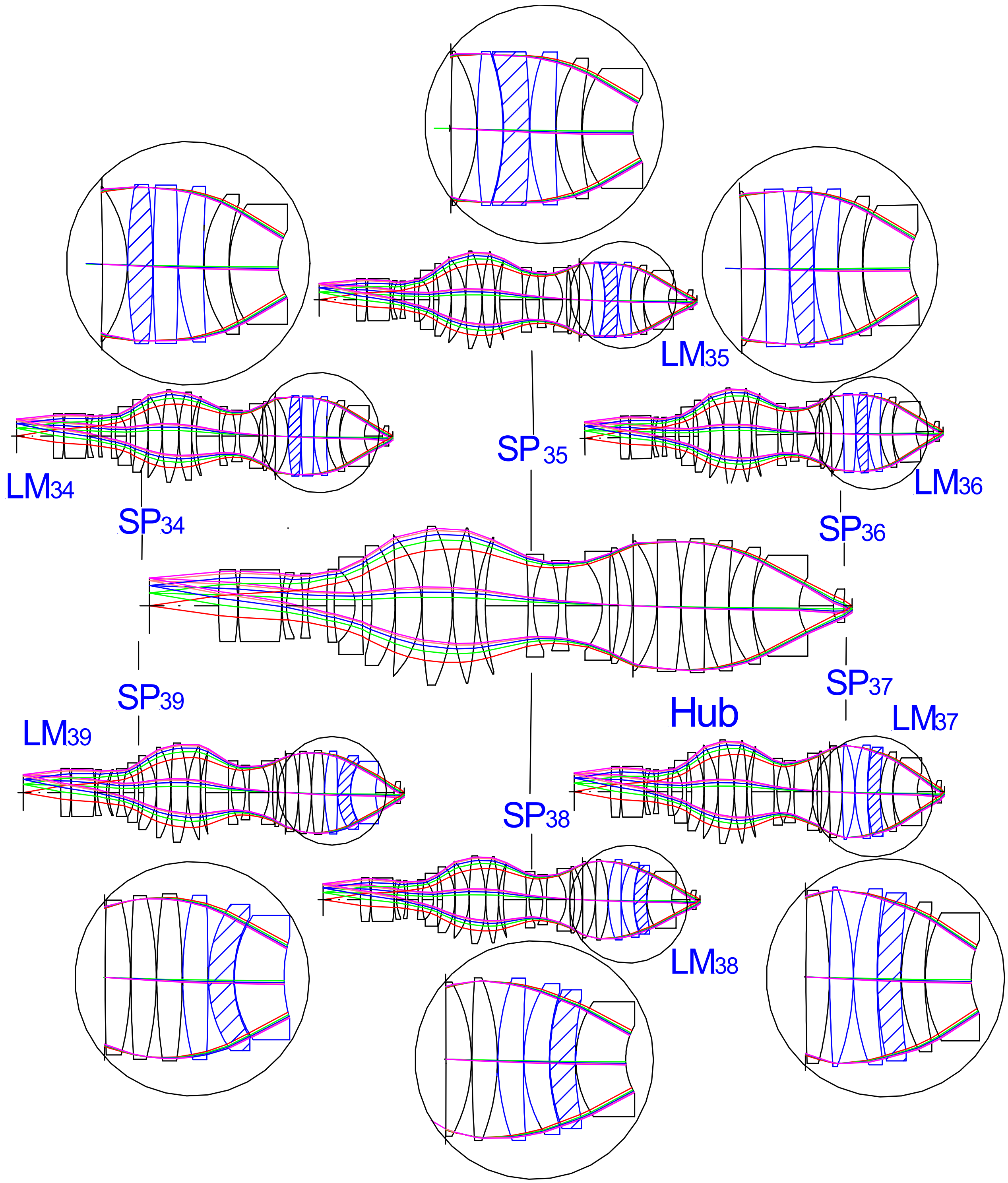

Fig. 3: Hub with six links in the network of local minima for a monochromatic lithographic objective with N+2 = 45 surfaces. For a better comparison, the part of the local minima where the most significant changes take place when inserting the meniscus is enlarged (encircled). The indices show the surface in the original system where an extra lens has been inserted and the new lens resulting from the meniscus is shown hatched.

Runs with a number of variables (18) reduced as mentioned above 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 fixed during these runs are, in fact, used only for polishing the final design.

3. DESIGN OF DEEP UV LITHOGRAPHIC OBJECTIVES

Constructing saddle points can be useful for design purposes. The goal of our research was to investigate whether by constructing saddle points, optimizing on the hub side (i.e. the side on which with the thin meniscus the merit function decreases less) and then removing lenses, we can reduce the number of lenses in lithographic systems without large departures from their initial performance.

The lithographic lens[5] presented in Fig. 4 consists of 47 spherical and aspherical surfaces, including the stop. All aspherical surfaces in the system are indicated with a thicker line. The numerical aperture is 0.85, the image height is 14.02 mm and the magnification is -0.25. The distortion is below 4.2 nm per field point. Reoptimized with a merit function based on wavefront aberration and with telecentricity and distortion control the system has a Strehl ratio of 0.999 or higher and a wavefront aberration of 3.67 mλ.

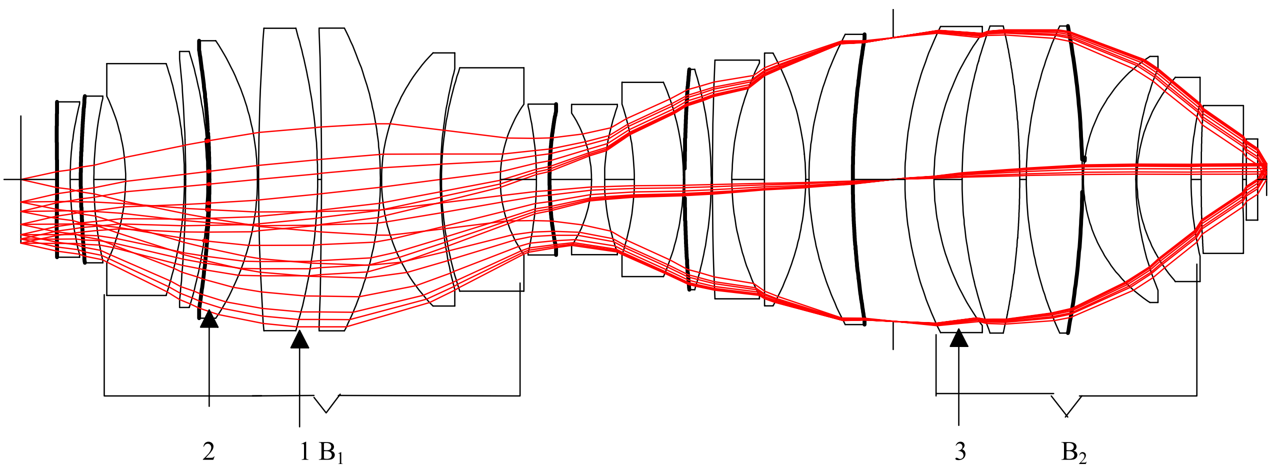

Fig. 4: 0.85 NA lithographic objective for 193 nm

The work has been done in the first bulge (B_1) and in the second bulge (B_2). In all this steps, distortion and telecentricity were kept within the same limits as for the starting design. For illustrating our method, the steps in the first bulge will be described in detail.

The first bulge, B_1, consists of seven lenses, having spherical and aspherical surfaces. All lens thicknesses have been made equal, as well as the distances between them. We have inserted a spherical meniscus at the position indicated by arrow 1 in Fig. 4 constructing, in this way, a saddle point. From the two local minima connected to this saddle point we have selected the one on the hub side of the saddle. From this configuration we have extracted the lens indicated by arrow 2 (which has an aspheric surface) and the spherical lens resulting from the meniscus we have introduced. The resulting minimum (Fig. 5) has two surfaces less than the starting system shown in Fig. 4. Moreover, it has one aspheric surface (described by seven aspheric coefficients) less. The wavefront aberration is 4.57 mλ, slightly larger than the one of the starting system, but this is also due to the fact that at this stage the thicknesses of the lenses in this bulge, as well as the distances between them don't have yet the correct value. The Strehl ratio (larger than 0.998) remains comparable.

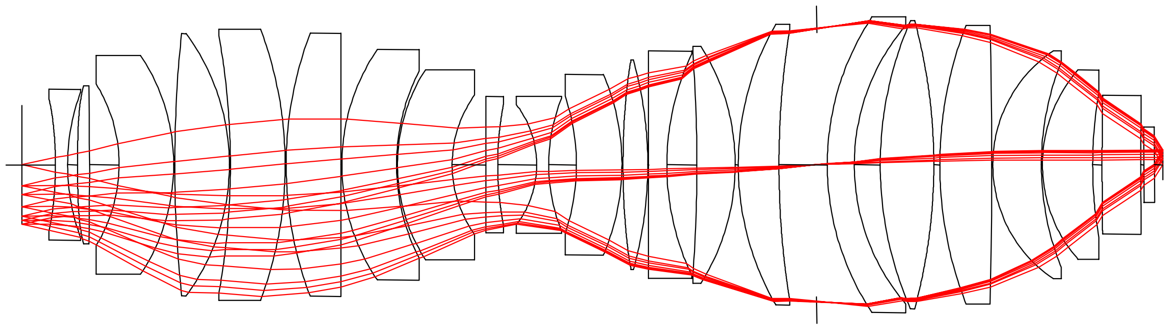

Fig. 5: The 0.85 NA lithographic objective after extracting from the first bulge a lens with an aspheric surface by eliminating the space between it and the previous lens.

When comparing the two configurations we observe that the most significant differences appear around the region where we have inserted the meniscus and extracted the lens (Fig. 6). As in Fig. 3 the rest of the lenses remain almost unchanged. This also supports the conjecture according to which changing a limited number of variables is sufficient to place the local optimization in the basin of attraction of a local minimum for all variables.

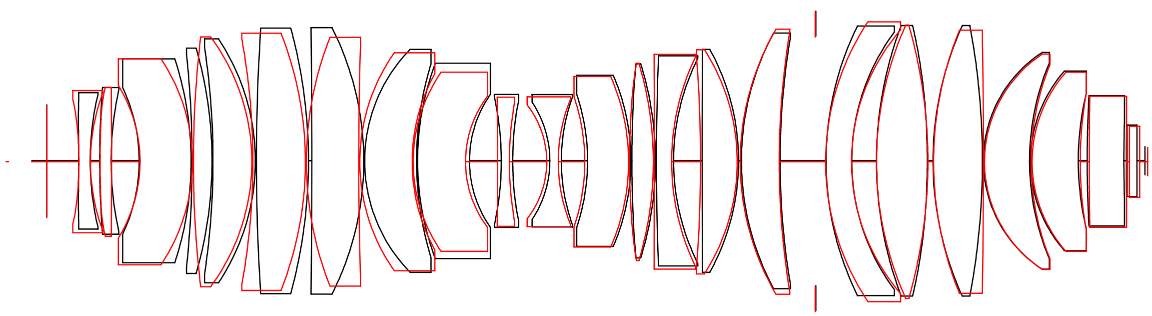

Fig. 6: Comparison between the starting system (Fig. 4) and the solution shown in Fig. 5. For facilitating comparison, the two system drawings are superimposed.

By applying in the second bulge a procedure which is similar to the one in the first bulge (we have inserted one meniscus) we have obtained configurations that allow us to extract three lenses from the system, including the very curved one indicated in Fig. 4 by arrow 3. The final design has a performance which is not worse, in terms of wavefront aberration, distortion telecentricity, and Strehl ratio than the starting system, but has three lenses and an aspheric surface less. Further details about this design will be given in a subsequent publication.

3. EXTREME UV LITHOGRAPHIC OBJECTIVES

We have also used the new method of constructing saddle points for ring-field mirror systems for EUV lithography. The method is illustrated with the following example. Starting with the four-mirror local minimum shown in Fig. 7 a), we have constructed a saddle point having six mirrors, by inserting a pair of mirrors after the first surface. As mentioned earlier both new distances are zero. The new saddle point leads to two local minima in the merit function space. We observe again that one of the local minima has a much higher merit function. (Again we call this side of the saddle the hub side.) After increasing the zero distances and optimizing, the two solutions take the shape shown in Fig. 7 b).

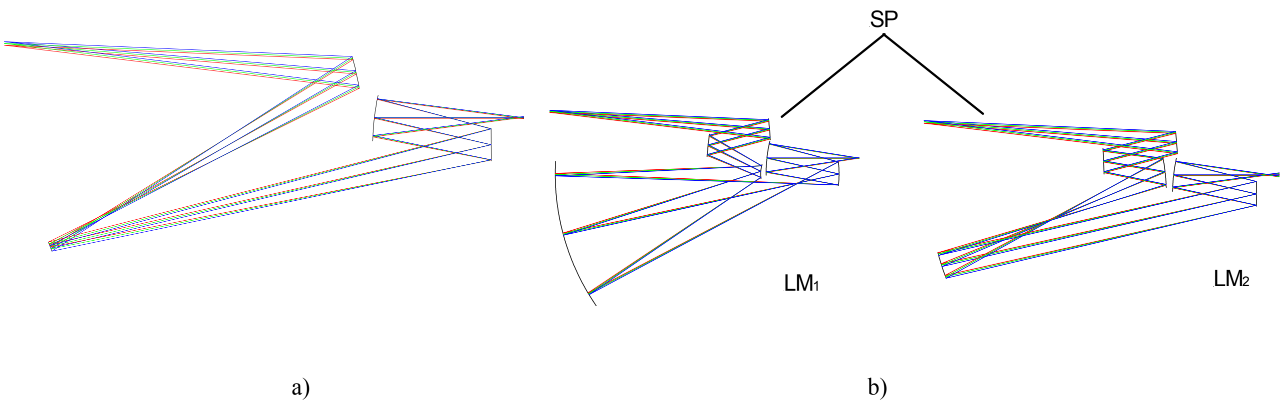

Fig. 7: EUV example: a) Starting local minimum (N = 4). At a numerical aperture of 0.16, the object heights are in-between 114 and 118 mm and the magnification is 0.25. b) EUV solutions resulting from a constructed SP at the first surface (N+2 = 6).

High-quality solutions can be obtained with this method. For instance, we have obtained an eight-mirror system from a six-mirror one with spherical surfaces. After locally optimizing the minimum on the hub side with all variables (curvatures, aspheric coefficients and distances) and practical constraints, we have reached a solution that satisfies practical requirements: distortion smaller than 1 nm and Strehl ratio larger than 0.995 with a wavefront aberration of 10 mλ. Further details about this design will be given in a subsequent publication.

In EUV design we have also successfully applied a generalized version of the saddle point construction method. At aspheric surfaces, saddle points are created by inserting a pair of mirrors with the same aspheric shape.

4. CONCLUSIONS

We have discussed the applicability of a newly developed method for generating saddle points with N+2 surfaces from a local minimum with N surfaces on deep UV lithographic objectives and extreme UV mirror systems.

We have shown the existence for lithographic objectives of a special type of local minima, the hubs, that are connected to more saddle points than usual local minima and we have shown how to generate them. A high-quality design for lithography at 248 nm is actually a hub. We have shown that our new method can produce new solutions in a simple, efficient and systematic manner. From a lithographic system at 193 nm, with 47 surfaces, we have extracted three lenses, one of them with an aspheric surface while keeping the performance comparable and we have obtained an eight-mirror extreme UV system that is adequate for practical applications.

5. ACKNOWLEDGEMENTS

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