Designing Lithographic Objectives by Constructing Saddle Points

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ABSTRACT

Optical designers often insert or split lenses in existing designs. Here, we present, with examples from Deep and Extreme UV lithography, an alternative method that consists of constructing saddle points and obtaining new local minima from them. The method is remarkable simple and can therefore be easily integrated with the traditional design techniques. It has significantly improved the productivity of the design process in all cases in which it has been applied so far.

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

1. INTRODUCTION

In the traditional design process of optical systems lenses are frequently inserted or splitted in existing configurations. An alternative way to achieve the same goals, which is based on constructing saddle points, has been recently presented1. When a lens is inserted so that a saddle point is constructed, two local minima are generated after optimization, whereas by inserting a lens in the traditional way, we always obtain a single local minimum. Then, the better of the two minima can be used for further design.

In a previous paper2 we have discussed some specific properties of the saddle point construction method when used to design complex optical systems, in particular for Deep UV (DUV) lithography. In this work, we present a new design for a DUV lithographic objective and we illustrate the applicability of the method for Extreme UV (EUV) lithography.

It has been previously shown3, 4 that from a certain type of saddle points (saddle points with Morse index 1), which are a straightforward multidimensional generalization of the well-known two-dimensional saddle point, by means of local optimization performed downwards on each of the two sides of the saddle, two local minima can be generated.

The central idea of saddle point construction is that at any position in a local minimum with N surfaces inserting a thin meniscus lens or two mirrors leads to a saddle point with Morse index 1 that has N+2 surfaces. Despite of the fact that nontrivial new insight into the design space is used, the method is remarkably simple and computationally efficient and can be applied to the design of systems of arbitrary complexity.

In this work, we first apply the saddle point construction method to the design of DUV lithographic objectives and show that, even for excellent designs, there can still be potential for further improvement. In these objectives all lenses are made of the same material. If the thin meniscus is in contact with the existing spherical surface where it is inserted and is made of the same material as the lens with that surface (the reference lens), the shape of the thin meniscus is particularly simple1: the curvatures of the two surfaces are identical with the curvature of the reference surface. 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.

Then, we show how the method can be used to generate EUV mirror designs.

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2. DESIGN OF DEEP UV LITHOGRAPHIC OBJECTIVES

In this section we show how constructing saddle points and then removing lenses from the local minimum with the better imaging performance, obtained from the saddle point, can result in lithographic objectives with a reduced number of lenses, but with a performance which is not worse than that of the initial system.

Figure 1 shows our starting system: a lithographic objective for 193 nm. The system has a numerical aperture of 0.85, the image height is 14.02 mm and the magnification is -0.25. Distortion is below 4.2 nm per field point and the wavefront aberration is 3.67 mλ.

In what follows, the system has been optimized with the optical design program CodeV with a merit function based on wavefront aberration. Distortion and telecentricity on the object and image sides have also been controlled.

In the first bulge, B1, all lens thicknesses have been made equal, as well as the distances between them. In contact with the surface indicated by arrow 1 a zero-thickness meniscus lens has been inserted to construct a saddle point. When letting the optimization roll down on the two sides of the saddle (for details see Ref.1), two local minima are generated. In each local minimum the thickness of the thin meniscus and the distance between it and the reference surface have been gradually increased to the same values as those of the other lenses in B1. We have continued the design with the solution having the best performance of the two, in terms of wavefront aberration. In this system it was then possible to extract the lens indicated with arrow 2 (that has an aspheric surface), as well as the spherical lens that has just been inserted. A strategy to extract lenses that was successful here 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 several steps to zero. The surfaces of the resulting thin lens are then made equal to the surface with which they are in contact. The required values of curvatures and distances are imposed as optimization targets during the subsequent reoptimization process. (This is in fact the reverse of the path from a constructed saddle point with a thin meniscus to a local minimum with all thicknesses finite.) Then, the thin meniscus thus obtained can be removed without affecting the system performance. The result is the design in Fig. 2 that has a lens (with an aspheric surface) less than the starting configuration shown in Fig. 1.

Fig. 1. The starting design is a 0.85 NA lithographic objective for 193 nm. Surfaces drawn with a thicker line are aspherical

Fig. 2. Lithographic objective obtained using saddle point construction in the first bulge
Next, a thin meniscus is inserted in the second bulge of the system, $B_2$ (see arrow 3). In the best local minimum connected to the constructed saddle point, we have merged the two lenses indicated with arrow 4. The resulting configuration allowed us to extract the lens 5, as well as to merge the two lenses showed in Fig. 1 with arrow 6. Finally, the system has been optimized with all parameters (curvatures, aspheric coefficients and distances) as variables.

The resulting design in Fig. 3 has three lenses less than the starting system shown in Fig. 1. Moreover, it has one aspheric surface (described by seven aspheric coefficients) less. Distortion is smaller than 1 nm and telecentricity is slightly better than that of the starting system. The wavefront aberration is 2.37 mλ, lower than that of the starting system.

The saddle point construction method has been also successfully used in the design of several other DUV lithographic objectives, including ones having a larger numerical aperture than that of the system presented in Fig. 1.

### 3. CONSTRUCTING SADDLE POINTS FOR EXTREME UV PROJECTION OPTICS

In this section we show how six- and eight-mirror EUV systems can be generated when starting from a local minimum with four mirrors (see Fig 4).

For simplicity, the four-mirror design selected as a starting point has all surfaces spherical ($m_4$ in Fig. 4). All four curvatures are varied. The numerical aperture is 0.16, the ring image height is 29.5 mm and the magnification is 0.25. The default CODE V merit function, based on transverse aberration, has been used for optimization. Constraints have been added to the merit function to control the telecentricity on the image side and the quasi-telecentricity on the object side.

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 the one where they have been introduced. The axial distances between the three consecutive mirrors is initially zero. From each saddle point, by means of local optimization, two new local minima are detected. When increasing the axial distances between the three consecutive mirrors, four solutions ($m_{6,S2A}$, $m_{6,S2B}$, $m_{6,S3A}$, $m_{6,S3B}$ in Fig. 4), having different shapes.

For both saddle points one of the minima with zero distances detected from the saddle point has a much larger merit function 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.

Further, we have used the solutions $m_{6,S2A}$ and $m_{6,S3A}$, the ones with the better imaging performance detected from $s_{6,2}$, respectively $s_{6,3}$, as starting points for the process of constructing new saddle points in $6 + 2 = 8$ mirrors. (The two local minima obtained after increasing the distances between mirrors in the solutions reached from the saddle point are referred to as solutions detected from the corresponding saddle point.)

We have inserted a pair of mirrors before the fifth surface in $m_{6,S2A}$, constructing the saddle point, $s_{8,5}$, that 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 have detected two solutions having eight mirrors ($m_{8,S2A}$ and $m_{8,S2B}$) from $m_{6,S5A}$. 

![Fig. 3. The 0.85 NA lithographic objective obtained after extracting three lenses and an asphere](image-url)
Surprisingly, both saddle points, $s_{6,2}$ and $s_{6,3}$, are connected on one side to the same solution. In fact, a further analysis shows that this solution, $m_8$, is connected in the merit function landscape to even more saddle points. Seven saddle points has been constructed by successively inserting the pair of mirrors as follows:

a) after the fourth surface, before and after the fifth and the sixth surface in $m_{6,S2A}$

b) after the first surface and before the second surface in $m_{6,S3A}$

On one side, all these saddle points lead to $m_8$.

Fig. 4. 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 system in the figure, the first subscript gives the number of mirrors, "s" indicates the saddle points 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"
Research in progress suggests that local minima in the optical design landscape that are linked, such as m₆, to a large number of saddle points (these minima are called "hubs"\(^1,2\)) are particularly interesting. For instance, the "hub" property seems to be correlated with relaxation.

Other examples of EUV saddle point construction are given in Figs. 5 and 6.

![Diagram](image.png)

**Fig. 5.** Other eight-mirror systems detected by constructing saddle points in six-mirror solutions of Fig. 4, which have poor imaging performance. A pair of mirrors has been inserted: a) before the second surface of m₆S₂A, b) before the third surface of m₆S₃A.

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 the one of the reference surface. As an example, a four-mirror system (see Fig. 6) having aspherical surfaces with aspheric coefficients going up to the 18-th order on each surface has been used as starting point. 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. 6 were obtained.

![Diagram](image.png)

**Fig. 6.** Solutions with \(4 + 2 = 6\) mirrors generated from a saddle point constructed from m₆. A pair of aspheric mirrors has been inserted before the third surface in m₆. 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.
4. DESIGN OF EXTREME UV PROJECTION SYSTEMS

In the previous section the emphasis was on the new method for EUV systems, rather than on optimizing the solutions presented there to satisfy practical requirements. However, high-quality designs can be obtained with this method also for mirror systems. For instance, we have obtained an eight-mirror system from a six-mirror one with spherical surfaces. In the system illustrated in Fig. 7 a pair of spherical mirrors has been inserted after the second surface. From the constructed saddle point, by means of local optimization two solutions have been generated, each having three consecutive mirrors in contact. After increasing the zero axial distances, the solutions have been locally optimized with all variables (curvatures, aspheric coefficients and distances) and practical constraints. In this way the two systems, \( m_{8,2A} \) and \( m_{8,2B} \), shown in Fig. 7 have been obtained. At this stage, the numerical aperture of the two solutions has been increased from 0.16 to 0.4.

![Diagram of system](image)

The solution, \( m_{8,2A} \), satisfies practical requirements: distortion smaller than 1 nm per field and Strehl ratio larger than 0.996 with a wavefront aberration of 10 m\( \lambda \). All surfaces are aspheric and the system has an intermediate image between mirrors four and five. The aperture stop is situated on the second mirror. During optimization, a constraint has been used to prevent obstruction but, in the last cycles of the optimization the freedom of obstruction constraint has been inactive. The final design is unobstructed. At the wafer side the system is telecentric, i.e. the chief ray is (approximately) perpendicular on the image plane. For coating related reasons, the angles of incidence of the chief ray at each surface have been kept smaller than 26 degrees, five of them below 15 degrees.

5. CONCLUSIONS

Recently, a method that uses saddle points in the design landscape has been proposed\(^1\) to generate efficiently new optical system configurations from known ones\(^2\). 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 can not be easily applied. The method can be easily integrated with traditional design techniques and is in fact a useful alternative to the traditional way of inserting or splitting lenses in existing designs.
So far, we have applied the new method in several designs of DUV dioptric and catadioptric lithographic objectives, and of EUV objectives. In all these cases, it has significantly improved our design productivity. In this paper, we have presented some of the results we have obtained. From a patented design of a high-quality DUV lithographic system at 193 nm, with 47 surfaces, three lenses have been removed, one of them having an aspheric surface, without deteriorating the performance of the final design in terms of wavefront aberration, Strehl ratio and distortion. An eight-mirror Extreme UV system that is adequate for practical applications has also been described.

6. ACKNOWLEDGEMENTS

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7. REFERENCES