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OPTIMIZATION TECHNIQUES APPLIED TO INITIAL DESIGNS OF ULTRAVIOLET LITHOGRAPHIC OBJECTIVES

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Abstract
The optimization of lithographic objectives is a quite challenging task due to many conflicting constraints, limitations and numerous variables. We describe the optimization techniques of starting designs for ultraviolet objectives which were previously generated by the global search algorithm. The powerful tools for the global optimization as Automatic Element Insert feature and Saddle points construction were applied to starting points, examining the applicability limited by design considerations. The ray tracing failures and critical lenses in starting designs caused by automatic decisions of the global search algorithm are fixed and replaced by Saddle point construction. The results of this work and presented techniques of the global optimization are valid and relevant for any on-axis complex optical system.

Keywords
global optimization, automated lens design, lithography, UV, global search algorithm, starting point

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МЕТОДЫ ОПТИМИЗАЦИИ ИСХОДНЫХ ОПТИЧЕСКИХ СХЕМ ЛИТОГРАФИЧЕСКИХ ОБЪЕКТИВОВ

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Аннотация
Оптимизация литографических объективов является сложной задачей из-за большого количества переменных и противоречивых ограничений. В работе приведено описание методов оптимизации исходных оптических схем для ультрафиолетовых объективов, сгенерированных на основе алгоритма глобального поиска. К исходным схемам применены эффективные инструменты глобальной оптимизации: функция автоматической вставки элементов и построение седловых точек с учетом конструктивных ограничений. Ошибки трассировки лучей и критические линзы в исходных оптических системах, выбранных автоматически с применением алгоритма глобального поиска, оптимизированы и

заменены с использованием метода седловых точек. Результаты работы и представленные методы глобальной оптимизации актуальны и применимы для любой центрированной сложной оптической системы.

Ключевые слова
глобальная оптимизация, автоматизированное проектирование линз, литография, УФ, алгоритм глобального поиска, исходная оптическая схема

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Introduction

In recent years, a several novel global optimization tools were developed and studied in lens design, proving that computational optimization of optical and photonics schemes is a blossoming field. The new algorithms and optimization features were implemented in lens design software as binary search Dsearch feature, AEI (automatic element insert) feature and Saddle point construction in Synopsys OSD, providing the optical designers with new useful optimization tools [1].

In the previous paper we described the method of successful starting point selection and design which play significant role in obtaining a high-quality lithographic objective [2]. Although, we obtained the starting points which closely resemble desired characteristics, the additional optimization is required to get the characteristics of diffraction-limited system. A correctly chosen starting point for further numerical optimization of the system provides an optical designer with various design parameter values within wide ranges, but the guidance on refining the quality and optimizations strategy is needed.

In the paper written by Marinescu, the method of optimization of existing deep-ultraviolet (DUV) lithographic objectives was proposed based on the theory of Saddle point construction [3]. By constructing Saddle points and obtaining resulting objective with reduced number of lenses, the applicability of Saddle point method in optimization of DUV lithographic objectives with good local minima has been proven. The conditions which should be fulfilled when applying the SPC are that all lenses are made of the same material in lithographic objective. It is related to the available variables and the theory behind the developed SPC method of global optimization.

Recent work of Z. Cao [4] has shown that SPC method can be used even in the development of starting points for lens groups of catadioptric DUV lithographic objectives. This research suggests that a promising approach is lens insertion in part of lithographic objective where the optical power and aberrations of the third and fifth orders play significant role. Accomplishment of task related to inserting the lenses is dependent on approach which determines the best position within the optical scheme [5]. The theoretical method of Lens form parameters, developed by Sasian and Descour [6], determines symmetry of the optical system and helps to determine optimum optical power. Method of lens form parameters can be applied to grouping design of lithographic objectives in order to find the best position to insert additional lens.

As the second approach, automatic element insert (AEI) feature of Synopsys OSD software can be used which is an automated lens design function and has embedded theories of Saddle point construction and the best position to insert lens [1]. In this work, we apply the Saddle point construction and AEI feature to starting point of ultraviolet (UV) lithographic objective showing that the global optimization strategy by these novel features for inserting and replacing lenses is successful optimization technique. As the main approach of lens insertion, we studied the effectiveness of AEI feature in the global optimization of starting points of UV lithographic objectives. Inserting two more lenses in lithographic objective with poor local minima of merit function (MF), we achieved diffraction limited system through further optimization

As another example we apply the Saddle point construction (SDC) [7] to UV lithographic objective successfully replacing the lenses with significant contribution of optical aberrations. Following the main goal to decrease the number of lenses, we normalized distribution of optical aberration in resulting lithographic objective, successfully switching the optical schemes from one to another global minimum.

Optimization of starting design by automatic element insert

The promising starting point (Fig. 1), assembled by 11 lenses of front part and 9 lenses of the rear part (image side), was selected for further optimization. Fig. 1 shows our starting system: a lithographic objective for the range of 362–368 nm, primary wavelength equal to 365 nm. This starting point was designed by the method explained in previous papers by generating two separate modules with glass model [2, 8].

The starting design for I-line objective has a F number of 1.25, the image height is 10.34 mm, distortion is below 0.1 % and the magnification is –0.2. Modulation transfer function shows that starting point has the potential to be optimized up to diffraction limit [9].

Therefore, it is necessary to introduce more variables to correct field curvature, distortion and chromatic aberrations causing poor image quality. In this case, we choose Automatic element insert (AEI) feature in order to introduce more variables by inserting lenses. AEI is a simplified form of saddle-point [1] construction which will be explained more in detail in the next section. This feature is intended for the case when there is a starting design already fairly well optimized and most of optimization parameters are already set up. On the other hand, the AEI is very useful in searching for the best place to insert a single element within such a starting point.

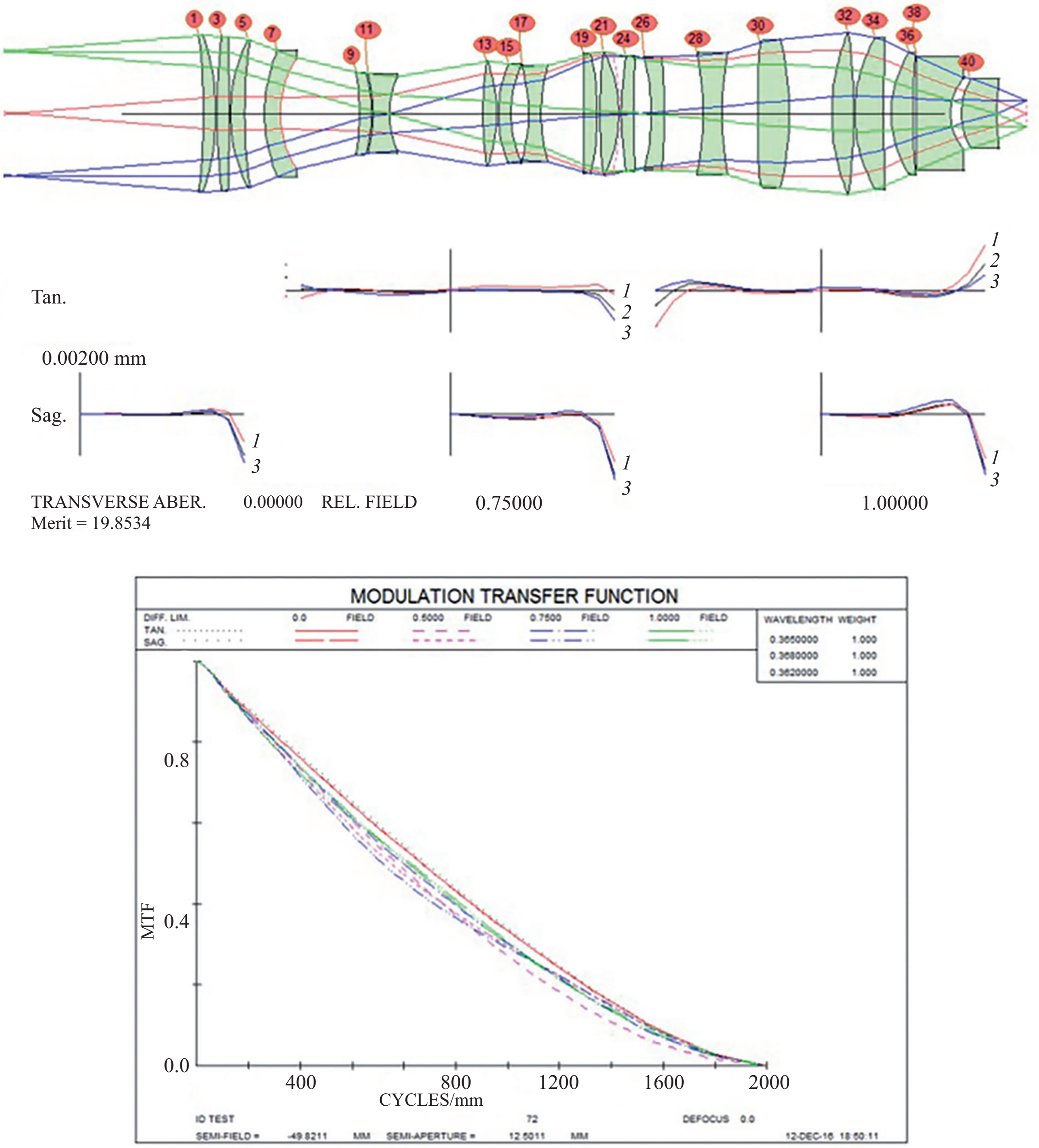

Fig. 1. Starting point with transvers aberrations and modulation transfer function

This AEI feature usually works with a glass model, but it is also possible to assign a real glass to the inserted lens by input parameters. The form of AEI is one command line in macros of Synopsys lens design software. Here we deal with the glass model with this input of future AEI 5 1 17 0 10000 0.2 inserted in already adjusted merit function macros.

The numbers after command AEI describe the next request:

5 – for library where resulting lens will be saved,

1 and 17 – for positions of the first and last surface which determine the part of objective where the feature will scan for the best place to insert one lens,

0 – specific command determining that we do not want cemented lens,

1000 – for starting value of radius curvature,

and 0.2 for starting value of thickness.

Note that we assigned the surfaces from 1 to 17, since we request AEI to insert lens somewhere in the front part of starting point (object side). In this way we want to force correction of field curvature and distortion which are significant on this side of the objective. Consequently, we determined the part of the objective where AEI search for the best position to insert one lens. Using the previously adjusted merit function we run the optimization with inserted command for AEI which initiates scanning of lithographic lens, searching for the best position to insert lens. Distortion and telecentricity on image side are being controlled within optimization macro. The AEI executes this task approximately in 10 min. (depends on computational power of PC) showing the output as the optimized objective with additional lens, requesting approval if we agree with a recommended position of inserted lens. We repeated two times the optimization with AEI feature, obtaining the optimized objective with glass models having two inserted lenses in waist on the image side (Fig. 2). The UV lithographic has been optimized with a merit function for optical path difference (OPD) and sagittal and meridional ray aberrations reaching diffraction-limit and wavefront aberrations of 27.24 mλ.

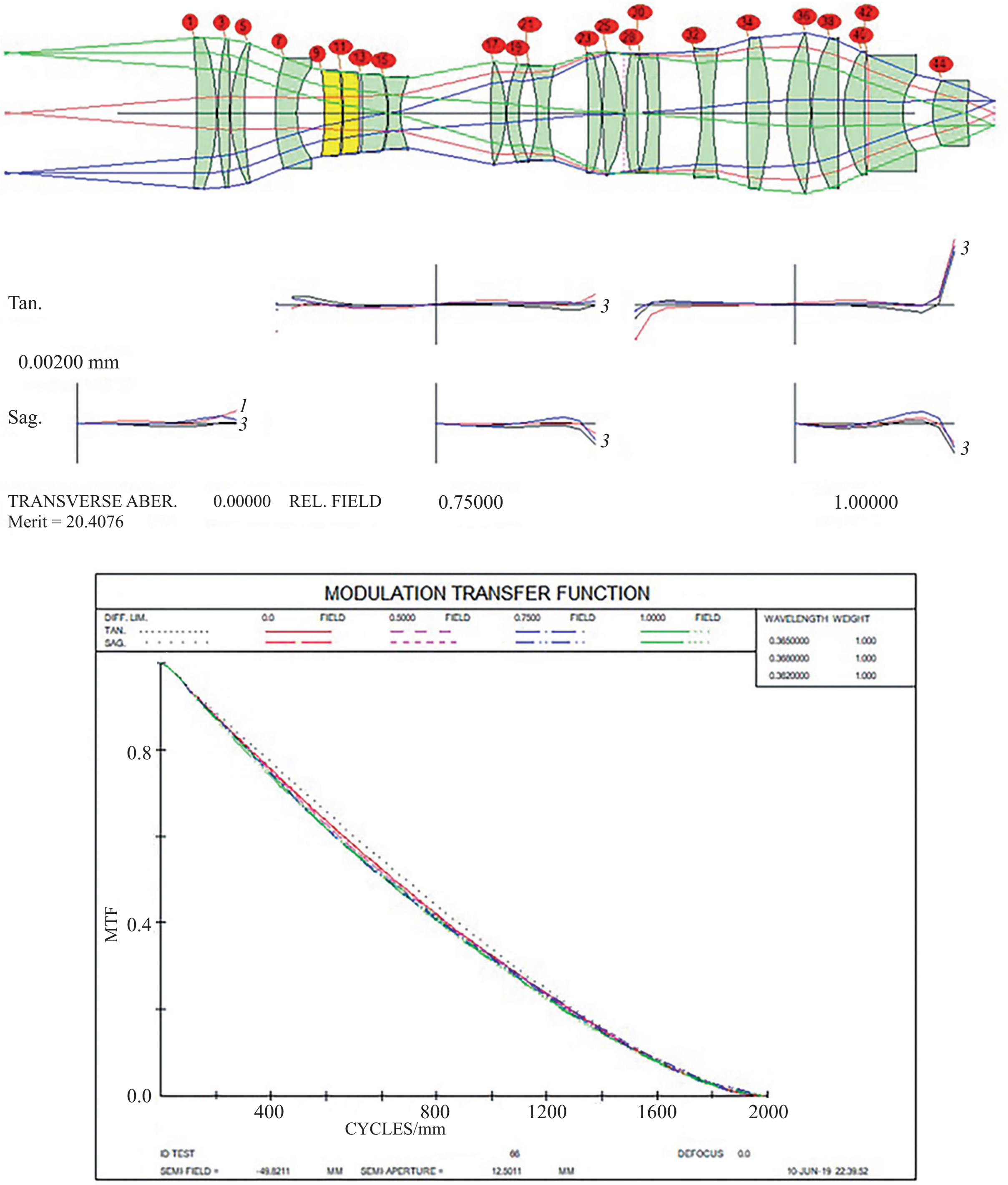

Fig. 2. Starting point with transvers aberrations and modulation transfer function after inserting two lenses by automatic element insert

The telecentricity on object side is kept by telecentric solve, while a telecentric chief ray on image side is controlled within the merit function [10]. Strehl ratio of resulting lens with glass model is higher than 0.98 for entire field of view (FOV) with similar distortion of 0.1 %. Next, using the ARGLASS function for automatic replacing of glass model, the glass model was substituted by glass material from I-line catalogue. The resulting objective with I-line glasses is shown in Fig. 2 with its MTF. Strehl ratio has been slightly decreased to minimal value of 0.946 on the edge of field for 365 nm. Computer simulation of image with image tools in Synopsys OSD is presented in Fig. 3. The simulation of three bars (0.5 um width) image with abberations shows fairly corrected lithographic objective on half and edge of FOV.

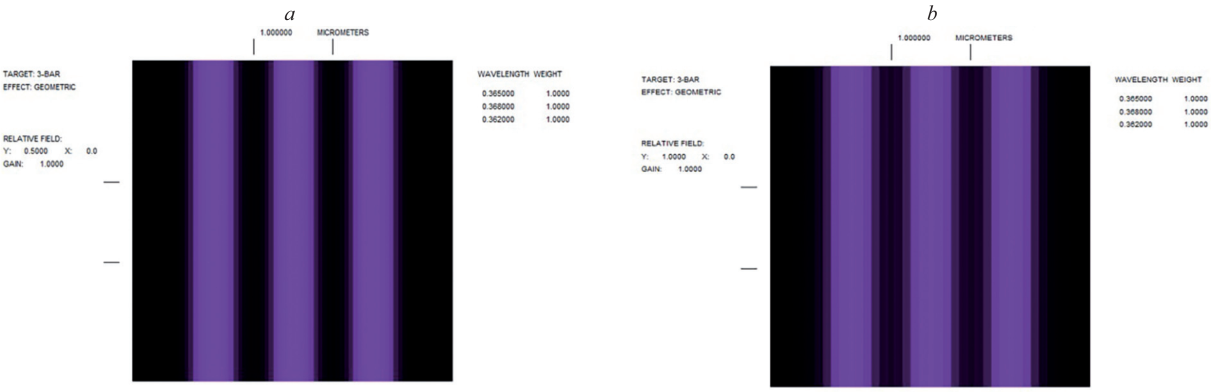

Fig. 3. Image simulation of ultraviolet lithographic objective: *a* — on the half of field of view, *b* — and one the edge of field of view

Optimization of starting design by Saddle point construction

In this section we examine advantages of saddle point construction (SPC), applied to starting design, switching the lithographic objective from one to another minimum, with a performance which is not worse than that of the initial configuration. Since we designed starting point for UV lithographic objective by the global search algorithm which automatically assembles lenses, the optical power and final order of negative and positive lenses were controlled by algorithm decisions.

Considering the main principle of Petzval sum correction [11], bulge-waist form, we used Saddle point construction to replace and move lenses with strong optical power which interrupt smooth path of ray tracing through optical system. The main idea of saddle point construction is that at any position in a local minimum of optical system with N surfaces inserting a thin meniscus lens creates the saddle point having N+2 surfaces. More in detail, SPC adds a thin shell at the selected side of lens, first with a small positive power and then with a negative power, and re-optimizes everything each time. Following this principle, a designer can decide to add negative or positive meniscus at the position where Saddle point (SP) was determined.

The Saddle point construction theory [7] is based on the idea of gradually inserting a lens with re-optimizing additional variables of curvatures in merit function (MF). Following this principle, the algorithm merely modifies the optical system in a continuous way to prevent radical changes in MF landscape. The possible inaccuracies in Saddle point search must be monitored by the gradient of merit function. Since we use all curvatures of lithographic objective as variables, stability and accuracy of Saddle point, caused by complexity of optimization, appears as a challenging task. The parameters of Saddle point scan in CODE V macro as delta gradient, and radius of curvatures must be previously adjusted for stable search of SP. Instability of Saddle point scan is mainly caused by numerical error in the gradient computation. Fig. 4 shows the MF gradient behavior in case of stable and unstable Saddle point scan in our initial configuration. Particularly, a scan of Saddle point was increased from regularly two to five points in order to stabilize Saddle point search.

A strategy for the further optimization of UV lithographic objective (Fig. 2) from previous section is that we identify points where ray tracing has sharp changes (radical changes in ray angle before and after lens surface) in order to replace the problematic lenses applying SPC method. First, we put data of UV objective from Synopsys OSD into CODE V lens design software for the further optimization. Then, we identify two lenses (Fig. 5, *a*) with the strongest negative power having the same glass PBM18Y ($N = 1.64$) as problematic ones for smooth ray path (marked by red).

From the left side of the surface indicated by arrow 21 a zero-thickness meniscus lens has been inserted to construct a saddle point (SPC). The further optimization of objective with saddle point meniscus created two local minima. The new local minima are created by gradually increasing the thickness of zero-thickness meniscus. Green meniscus in Fig. 5, *b* is a new lens created (inserted) by SPC.

Fig. 6. illustrates the value of merit function while the new lens has been inserted creating new local minima with inserted meniscus.

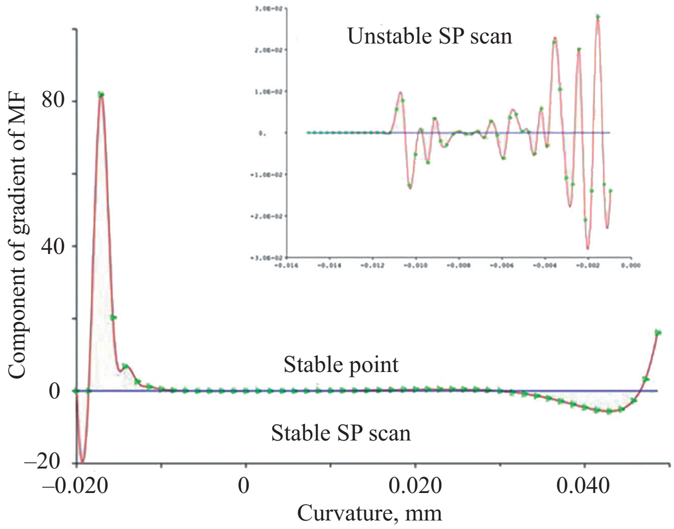

Fig. 4. Stable and unstable Saddle point scan

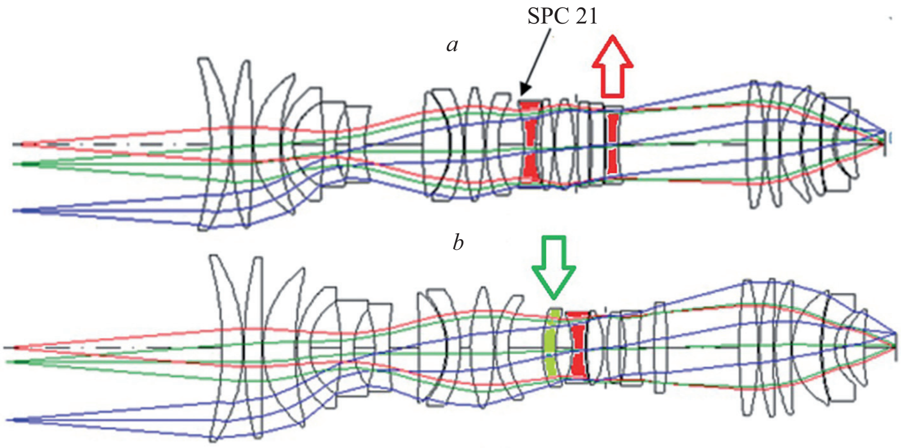

Fig. 5. Ultraviolet lithographic objective obtained using saddle point construction: *a* — before extraction of lens, *b* — after inserting meniscus

In order to keep the same number of lenses, we decide to extract the lens with negative power on position 16 by using the macro for extracting the lens. The macro for lens extraction is accomplishing task by gradually decreasing the thickness and correcting the curvatures of selected lens which leads to the null element.

More specifically, 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 they are in contact with.

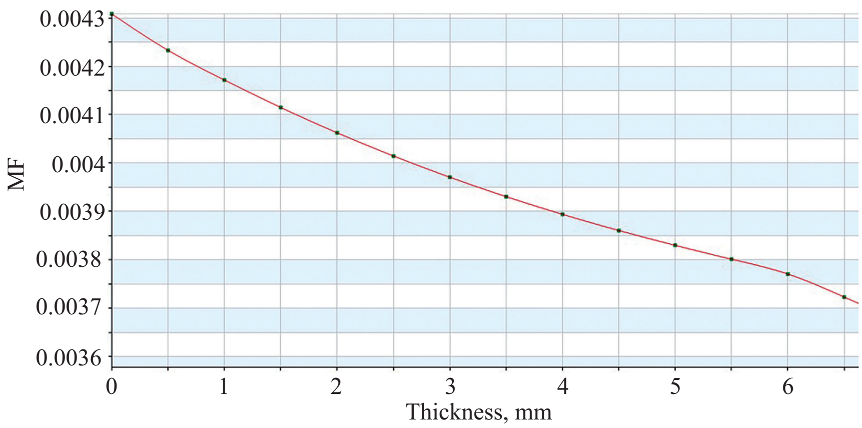

Fig. 6. Merit function value dependence on thickness of inserted lens in generating of local minima

Then, the thin meniscus, thus obtained, can be removed without affecting the system performance.

Finally, the system has been optimized with all parameters (curvatures and distances) as variables.

The result is the design in Fig. 5, *b* that has smoother ray tracing and better distribution of lenses in bulge waist shape. The resulting UV objective has better correction of distortion below 0.01 % (Fig. 7), while the field curvature kept the similar values, with slightly better wavefront aberration of 17.55 mλ.

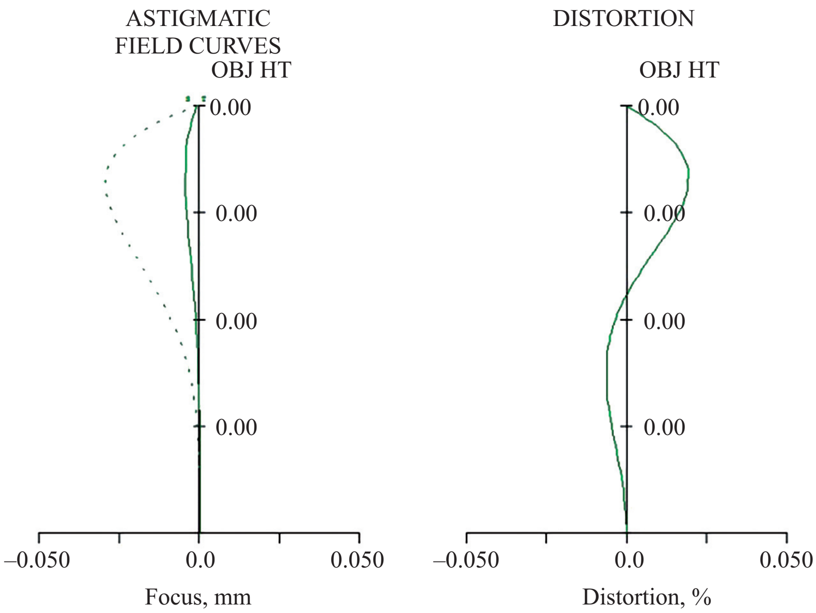

Fig. 7. Field curvature and distortion of optimized ultraviolet lithographic objective

In the second approach, the distribution of the third-order aberration coefficients was studied. As we already know, surfaces with high spherical aberrations are more sensitive to defects during manufacture. Therefore, the main objective was to improve the distribution of the third-order spherical aberrations and the distribution of the other third-order optical aberrations [12]. A lithographic lens was chosen (Fig. 8, *a*) (wavefront aberration of 20.86 mλ) for the further optimization. The graph of the coefficients shows that there are surfaces with high spherical aberrations of the third order (see red arrows), tangential astigmatism and tangential coma.

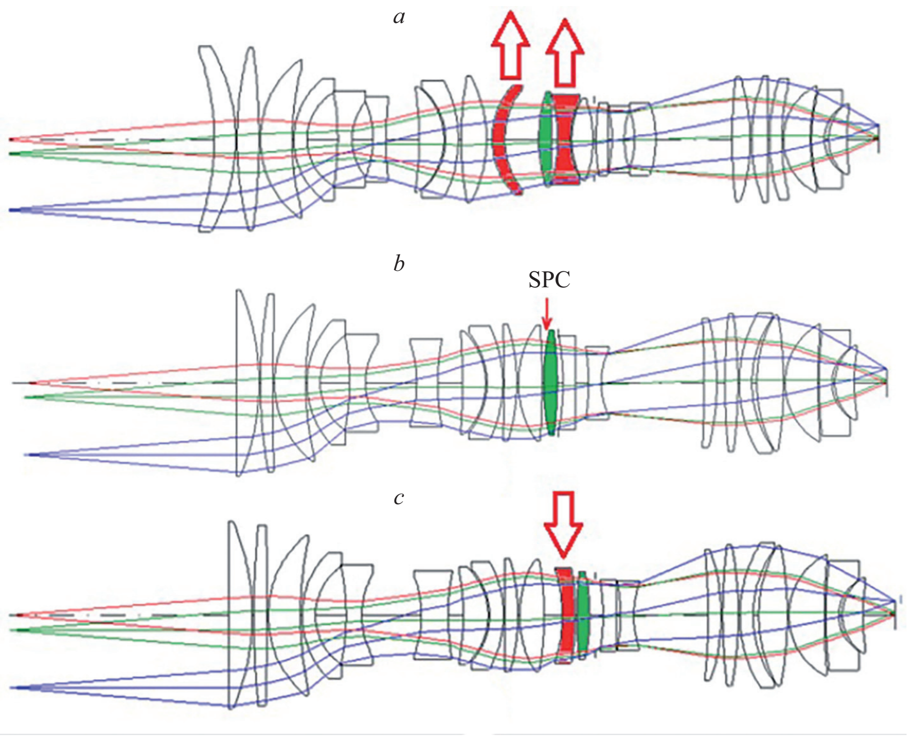

Fig. 8. Optimization of ultraviolet lithographic objective: *a* — initial configuration, *b* — after lens extraction — Saddle point; *c* — obtaining Saddle point minima

Both selected, critical lenses have PBM18Y glass material with the highest refractive index in I-line catalogue. It was decided to extract the two negative lenses marked in red using a macro to extract lenses which create a zero lens element [13]. First, we extract the negative lens number 12 (red color) from UV objective (Fig. 8, *a*) and, secondly, we extract lens with negative power number 10 scanning for the saddle point at the same time.

The resulting UV lithographic objective with 20 lenses essentially represents the configuration of Saddle point (Fig. 8, *b*). It has a wavefront aberration of 25.67 mλ, with slightly spoiled correction of Petzwal curvature [14]. The new values of Petzval curvature and chromatic aberrations are affected by the extraction of negative lenses from PBM18Y glass material. Next, from the left side of the lens marked by green color (Fig. 8, *b*), a zero-thickness meniscus lens has been inserted to construct a saddle point (SPC). Red meniscus (Fig. 8, *c*) is the new lens (local minima) created by SPC. If we pay attention to the spherical aberrations of critical lens group (negative power) we note that aberrations are reduced comparing to the Seidel coefficients of initial configuration (see red arrows) (Fig. 9). Generally, the Seidel coefficients of the spherical aberrations along the UV objective show a much more relaxed distribution of the optical aberrations comparing to initial configuration (Fig. 9, *a*) [15].

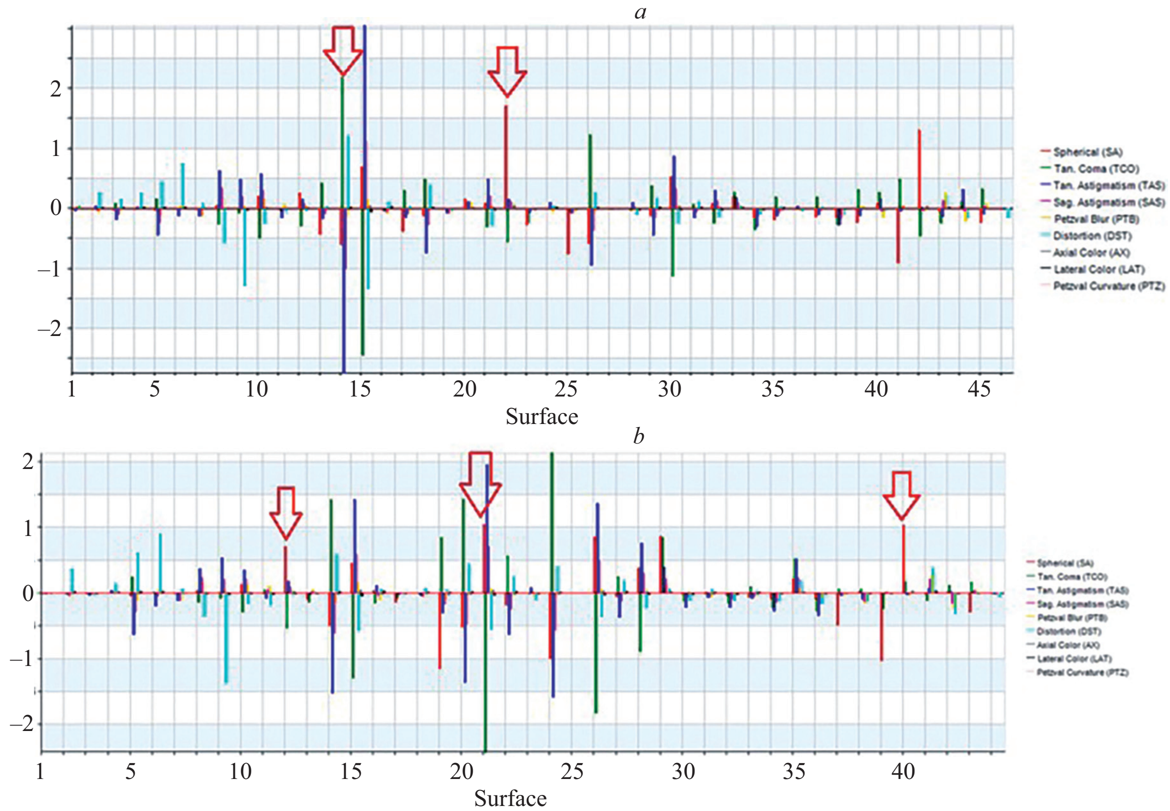

Fig. 9. Distribution of Seidel coefficients: *a* — initial configuration, *b* — after optimization by Saddle Point Construction

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

The resulting ultraviolet objective has 21 lenses (one less than the initial design) with wavefront aberrations of 22.93 mλ, and less sensitive lenses for fabrication, considering the third-order spherical aberrations and tangential coma.

Conclussions

In this paper, the optimization features for automatic element insertion were successfully applied to the initial configurations of ultraviolet lithographic objectives. We have shown the effectiveness of novel techniques of inserting elements in complex systems as an effective enhancement of traditional ways. By automatic element insert feature diffraction-limited system and good image quality have been achieved.

The study on Saddle point construction method has been performed in collaboration with the colleagues from the Delft University of Technology, Delft, according to the specific requirements of lithographic objectives and the authors' observations. The authors were particularly resolving the issues caused by automatic computer decisions and were fixing the problems generated at the stage of the starting points. The results of presented optimization technique with Saddle point construction show new method feature: the surfaces with large contribution of aberrations can be replaced by switching the initial configurations assembled by the global search. Consequently, the ray tracing failures and technological characteristics of starting points were optimized with proven computational efficiency. Essentially, optimization by Saddle Point Construction method and Automatic Element Insert feature provided for stabile and accurate optimization of initial configurations previously generated by the global search algorithm.

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