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Research Article

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Design of an ultraviolet projection lens by using a global search algorithm and computer optimization

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Abstract: This paper describes a method for designing an ultraviolet (UV) projection lens for microlithography. Our approach for meeting this objective is to use a starting design automatically obtained by the DSEARCH feature in the SYNOPSYS™ lens design program. We describe the steps for getting a desired starting point for the projection lens and discuss optimization problems unique to this system, where the two parts of the projection lens are designed independently.

Keywords: global optimization; lithography; optical design; projection lens; starting point; UV.

1 Introduction

Optical lithography is a photographic process of using an optical image and photosensitive film to produce patterned silicon wafers in semiconductor manufacturing. Numerous technologies have been proposed and developed to improve the performance of optical lithography, but so far none has succeeded in replacing optical lithography [1].

One of the most challenging steps for an optical designer is how to start designing an optical system. Usually, a successful optical design depends on the selection of a successful starting point. If the selected layout has enough correction potential, the optical designer can shorten the overall time of work and reach the design goals more quickly. Therefore, optical design software vendors are starting to provide users with tools that can automatically select the starting layout for the design process.

One of David Shafer’s papers, *Doing More With Less*, says that achieving even higher-performance levels in optical design does not always require going to more cost and complexity in the design. Often, it is possible to make major performance improvements by changing assumptions at the very beginning of the design process [2]. Using such a design philosophy, new methods of optical design can be developed. Successfully choosing the starting design at the early stages of development significantly shortens the overall design time. As computers were first applied to the field of optical design, the speed of ray tracing has increased a thousand fold, while the speed with which new schemes can be created has increased only about two to three times [3].

Figure 1 shows one type of projection optical lithography system. The source of ultraviolet (UV) light is a laser that shines through the illuminator, which expands, homogenizes, and conditions the beam in the condenser. Then, the light goes through a photomask and the projection lens to the wafer, which is coated with a photosensitive film [4].

The driving forces for lithographic systems are a decrease in wavelength and increase in the numerical aperture, while the solution space is limited by several conflicting constraints such as diffraction-limited performance, reasonable overall dimensions, minimum number of optical elements, availability of material, and limits on the angles [5].

Lithographic objectives are famous for their high quality and for the many challenges they present in optimization. In this paper, we propose a method for developing an UV lithographic projection lens that can simplify the work of the optical designer at an early stage of the design.

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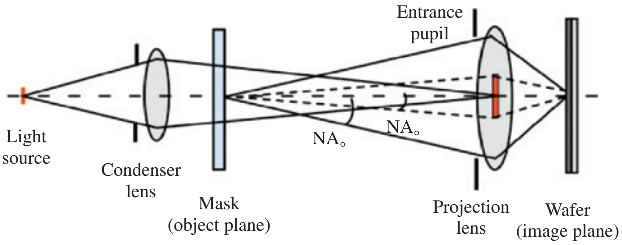

Figure 1: Schematic of the lithographic optical system.

We have divided the element set of a lithographic lens into two parts:

- The front part, with the external exit pupil, which is understood as a reversed lens with an external entrance pupil.
- A rear part, with the external entrance pupil (Figure 1).

Both parts can be designed independently as two (photo) objectives with the external entrance pupil and with the constraint of a telecentric chief ray. Each part of the lithographic optical system must be optimized as well as possible in order to achieve diffraction-limited optical performance. We have taken the specifications for a proposed optical system from a reference UV lithographic objective [6].

Figure 2 shows our reference UV projection system (Simax System Development B.V. Eindhoven): a lithographic, bi-telecentric objective for 365 nm with aberrations corrected up to the diffraction limit. The following characteristics define the projection system: 19 lenses, F/number 1.25, Gaussian image height 10 mm, image distance 22 mm, Strehl ratio 0.986 for the Principal color, and magnification – 0.2.

The spectral range of the lithographic lens is in the UV with wavelengths 362 nm, 365 nm, and 368 nm; the principal color is 365 nm. At the stop location, where the chief ray has a small value, we divided the system into two parts.

The starting points for the rear and front parts of the UV lithographic system were obtained by the design search feature DSEARCH of the SYNOPSYS™ lens design program and optimized in the merit function using ray and pupil aberrations in the same software [7].

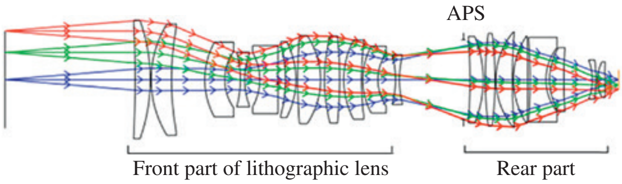

Figure 2: Schematic of the reference UV projection lens.

The independently designed parts with glass models were then combined into one lithographic objective in SYNOPSYS and further optimized. When the design was deemed satisfactory, it was submitted to the automatic real glass feature of SYNOPSYS, ARGLASS. This algorithm finds the closest real glass to each of the model glasses, subject to filter criteria such as cost, chemical stability, and the like, and reoptimizes the lens after substituting that glass for the model. When it has finished, all glasses in the design are real glasses from the glass tables.

Final aberration control and correction and MTF (modulation transfer function) optimization of the total projection UV lithographic lens were also done in SYNOPSYS™, and reached the diffraction limit.

2 Starting design of the lithographic objective

In order to obtain a successful starting point for UV projection lens, we have been using DSEARCH (design search) feature in the Synopsys software.

This algorithm applies a novel insight to the design problem: we note that, from the top of a mountain, one can see all the valleys in the region – and that is the only place from which they can be seen. The top of a mountain corresponds, in optical terms, to a lens made of plane-parallel plates. Such a design can go anywhere, and by sliding down the mountain in a given direction, one can find a valley in that direction. By a clever choice of directions, one hopes to find all of them. The lowest valley is the best lens.

DSEARCH uses a search method based on a binary number, each bit corresponding to a lens element, the power of the element either positive or negative according to the value of that bit. By cycling through all the values of the binary number and optimizing the lens in that direction, one can quickly evaluate all combinations of lens power. Thus, a four-element lens created with number 0000 would have all negative elements, while 0001 would produce a lens with one positive element, and so on. In this manner, the program carries out a fast and efficient search of the entire design space.

As this space can be extensive, and we would like the process to execute as quickly as possible, we divide the task into two phases. In the first phase, we do a quick evaluation of the lens in a given direction, employing a merit function that consists on only third- and fifth-order aberrations, plus three real rays (to avoid solutions that lead to ray failures). This quick mode runs in only a few minutes and is followed by further optimization of the 10 best solutions that resulted, using a more conventional merit function that corrects a larger grid of rays. All lens radii and thicknesses are varied except the last (if they are controlled by paraxial solves to constrain the F/number and defocus), and all glass properties are allowed to vary in order to find the location on the glass chart where the lens works best [8].

The process can optionally submit each design to an annealing phase, where the program makes small random changes to the design variables and reoptimizes, over and over. This ensures that it finds the lowest valley in that direction. When it has finished, the 10 best solutions are saved as disk files that can be opened by the user for further investigation.

2.1 Starting design of the rear part of the lithographic objective

To maintain the specifications of the reference lithographic optical system, the rear part of the lens has been designed with derived specifications from that objective. For this reason, the focal length of the rear part, 100 mm, was chosen in order to maintain the total track length of the lithographic objective. At the same time, we have made a compromise, achieving a smaller field of view – ω in Eq. (1).

$$\omega = \arctan\left(\frac{y'}{f'}\right) = \arctan\left(\frac{9{,}96}{100}\right) = 5{,}69 \tag{1}$$

$$\mathrm{FN} = \frac{f}{\mathrm{DN}} \rightarrow \mathrm{DN} = \frac{f}{\mathrm{FN}} = \frac{100}{1{,}2} = 83{,}33 \tag{2}$$

Marginal ray height (half of nominal diameter DN) required for DSEARCH, is derived by Eq. (2). Table 1 shows the specifications for the starting point of our projection lens. The number of elements (lenses) was chosen after the several design trials. We tried various numbers of elements, which is an input parameter to DSEARCH. A smaller number executes more quickly but requires more effort afterward, as one approaches a final design by repeated optimization and adding elements where necessary with the AEI feature of SYNOPSYS, which uses the ‘saddle-point’ theory of Florian Bociort [9].

Table 1: Specifications for the starting point of design.

Specification	Value
Object distance	Infinite
Object height	Infinite
Marginal ray height, DN/2	41.67 mm
F/number	1.25
Field of view, ω	5.69°
Focal length, f	100 mm
Gaussian image height, y'	10 mm
Image distance	22 mm

In the input to DSEARCH, we have defined the targets of our system and specified a number of parameters, such as the number of elements, the number of passes through the search space, and how to control optical aberrations. This input is shown below.

```
LOG
CORE 8
DSEARCH 5 QUIET
SYSTEM
ID LITHOGRAPHIC REAR
OBB 0 5.69 41.667
UNI MM
WAVL .368 .365 .362
END
GOALS
ELEMENTS 15
TOTL 450 0.1
FNUM 1.2 10
BACK 22 100
THSTART 10
RSTART 1250
NPASS 80
ANNEAL 100 25 Q
SNAP 10
STOP FIRST
STOP FIX
QUICK 50100 ! quick optimization
FOV 0 .75 .9 1.
FWT 2 1 1 1
END
SPECIAL PANT
CBOUNDS 1.88 6.43 1.49 83.55
FBOUNDS 1.92 22.16 1.50 62.67
CUL 1.6 !refractive index limits
FUL 1.6 !for glass model
END
SPECIAL AANT
ACM 10 1 1
ACC 28 1 1
M 0 10 A P HH 1 ! telecentricity
M -.001 10 A P HH .5
M -.001 10 A P HH 1! pupil aberr.
```

```
M 0 1 A P YA 1! distortion
S GIHT
END
GO
```

Section OBB 0 5.69 41.667 in the above input specifies a field angle of 5.69 and a marginal ray height 41.667. The input WAVL 0.368 0.365 0.362 defines the required spectral range; in the GOALS section, we define the general requirements of the lens: the number of lenses (ELEMENTS 15), total length in millimeters (TOTL 450), the F/number (FNUM 1.2), and the back focal distance (BACK 22). We emphasize here that it is very important to pay attention to weights, especially in the GOALS section. Changing these weights leads to different shapes and transverse aberrations of the resulting designs. Next is the section that defines the number of passes and the temperature of the simulated annealing phase. This statistical method is motivated by the physical equilibrium that is attained in the cooling of substances. It is often successful in solving combinatorial optimization problems [10].

We put the aperture stop at the first surface (STOP FIRST), and do not let it move (STOP FIXED); we also define the minimum and maximum element thicknesses (ACM 10 1 1, ACC 28 1 1) that bring our design closer to reality. Within the section SPECIAL AANT, the particular constraints for telecentricity, the pupil aberrations, and distortion are defined, respectively.

The UV spectrum of light limits the design of UV optical systems for reasons related to the properties of existing materials and their internal transmission [11]. At the same time, it is very useful to allow the program to find the best combinations.

During the initial optimization phases, we allow the glass model to vary, as noted above, and constrain the region of the glass map to that area in which glasses suitable for the UV are to be found. The software accepts input parameters defining this region, for example, CBOUNDS (crown limit) 1.88 6.43 1.49 83.55, which describes a line from the point N = 1.88, V = 6.43 to the point N = 1.49, V = 83.55. The UV glasses are all found to the right of this line. A similar input describes the boundary on the right side, in this case defined as a curve where those glasses are all found to the left.

In this way, the algorithm is free to choose any material in the glass catalog from the area where the i-Line glasses are located.

Using this technique, it is possible to try different weights for the design goals. In our case, the estimated time was around 10 h for DSEARCH to find the 10 best candidates to use as starting points for the design.

The 10 starting designs for the rear part of the lithographic objective found in one DSEARCH attempt are shown in Figure 3. It is evident that the algorithm has already proposed a logical shape for the second part of the lithographic objective, with the more positive lenses in the bulge of the system. Owing to the low weights assigned to some constraints, the first two starting points proved unsuitable. Another condition in selecting the design is that our starting layout should have the smallest transverse aberration of all the 10 designs. Applying that condition, we are left with four qualified starting points: DS3, DS4, DS8, and DS9.

A general issue in optical design is to minimize the aberrations over a given spectral range within a specified field of view for an aperture size required to gather adequate light [12]. An additional condition regarding the choice of a starting design is related to the location of lenses having negative power and the magnitude of their third-order spherical aberration. Each design has few negative-powered surfaces, which contribute positive spherical aberration. The lenses (surfaces) with large aberrations are, in general, more sensitive to manufacturing errors because the ray angle of incidence is relatively large [13].

Considering the above-mentioned criteria, the final chosen starting point is DS3, shown in Figure 4, having 11 positive elements out of a total of 15 elements, with transverse aberrations in the range of 0.002 mm.

The starting design for the rear part was optimized up to the point where all optical aberrations were decreased as far as practical (Table 2). It is unrealistic to expect to

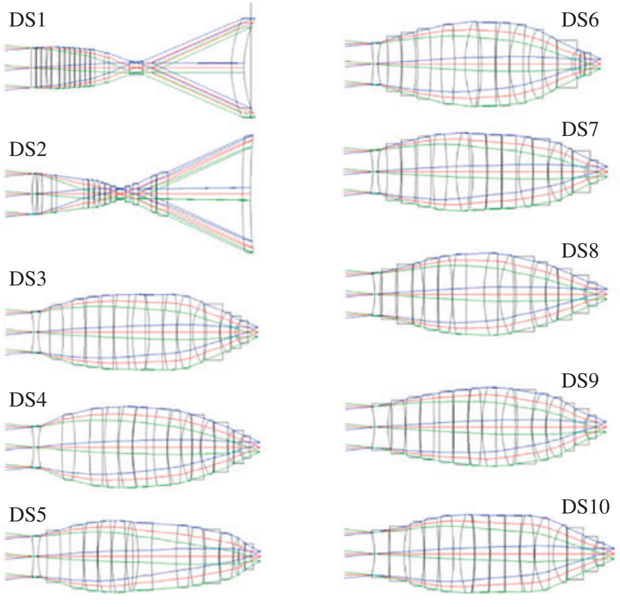

Figure 3: Starting designs obtained by DSEARCH.

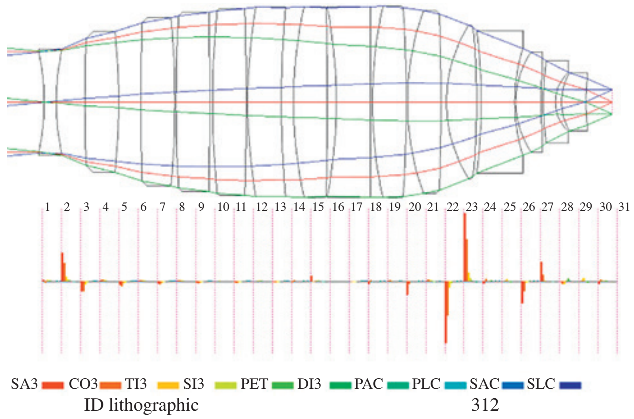

Figure 4: Designed rear part of the lithographic objective with distribution of third-order aberrations.

easily reach a diffraction-limited system consisting of 30 spherical surfaces with the F/number and constraints we are after. The next step in our design strategy was introducing more corrective variables by connecting the rear part with the front part of the UV lithographic objective.

2.2 Starting design of front part of UV lithographic objective

The front part of the lithographic objective that we designed with the help of DSEARCH has to be understood as a reversed lens with the external entrance pupil.

The final design has to be reversed in order to get the object height of 50 mm and finite object distance of 150 mm. In the front part of the objective, we keep the same marginal ray height where the parts are to be connected and the same field of view as the rear part of lens. The focal length and F/number are automatically determined by these requirements.

Table 3 presents the specifications of the front part of the lithographic objective. The relatively large F/number of six makes the design of a diffraction-limited system in the front part easier, and it behaves actually like a new complex corrective element in the total optical system.

The estimated search time is around 20 min to execute the data of DSEARCH shown below in one attempt.

```
LOG
CORE 8
DSEARCH 5 QUIET
SYSTEM
ID LITHOGRAPHIC FRONT
OBB 0 5.69 41.667
UNI MM
WAVL .368 .365 .362
END
GOALS
ELEMENTS 10
TOTL 330 0.1
FNUM 6 10
BACK 150 100
THSTART 10
RSTART 1250
NPASS 80
ANNEAL 100 25 Q
SNAP 10
STOP FIRST
STOP FIX
QUICK 10 20 ! quick optimization
FOV 0 .75 .9 1.
FWT 2 1 1 1
END
SPECIAL PANT
CBOUNDS 1.88 6.43 1.49 83.55
FBOUNDS 1.92 22.16 1.50 62.67
CUL 1.6 !refractive index limits
FUL 1.6
END
SPECIAL AANT
ACM 10 1 1
ACC 23 1 1
M 0 10 A P HH 1 ! telecentricity
M -.001 1 A P HH .5 ! pupil aberr.
M -.001 1 A P HH 1
END
GO
```

The method of selecting the starting design for the front part of the objective was similar to the method explained above for the rear part.

Table 2: Third-order aberrations of starting point.

Sph. Aberr.	Coma	Tang. Astig.	Sagittal Astig.	Petzval	Distortion
(SA3)	(CO3)	(TI3)	(SI3)	(PETZ)	(DI3(FR))
0.0062	0.0156	– 0.00845	– 0.01256	– 0.01462	– 0.00091

Table 3: Specifications for the starting point of design.

Specification	Value
Object distance	Infinite
Object height	Infinite
Marginal ray height, DN/2	41.67 mm
F/number	6
Field of view, ω	5.69°
Focal length, f	500 mm
Gaussian image height, y′	50 mm
Image distance	150 mm

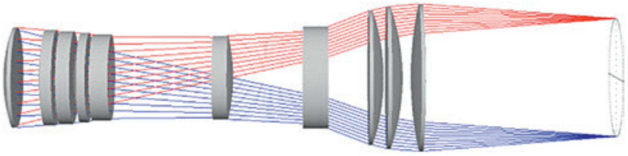

Figure 5: Designed reversed front part of lithographic objective.

Figure 5 shows the designed, reversed front part of the lithographic objective, which was optimized up to the diffraction limit.

3 Constraints and optimization of UV lithographic objective

When one combines two parts of an objective into one optical system, one has to consider that one section is focal and the other afocal, and also pay attention to the definition of the aperture stop. The reversed front part of the lithographic objective was connected with the rear part by the commands REVERSE and COMBINE (according to the SYNOPSYS user's manual).

Before we switch to a design-related topic, we would like to discuss briefly issues related to the main constraints: telecentricity and distortion. Perfect telecentricity on the object side can be achieved by keeping the telecentric-object solve (TCO), otherwise a real-iterative pupil should be chosen, while double telecentricity (a telecentric lens on, but the object and image side) is controlled by the optical designer.

The fact is that the distortion is proportional to the pupil spherical aberration in the exit pupil. It means that if the distortion is to be independent of the object position (telecentricity in object side), then the spherical pupil aberration must be decreased to zero [14]. Thus, the distortion in our case has to be kept close to zero, while the values of the exit and entrance pupil positions are managed by the art of compromise in optical design.

In this case, the optical design required a compromise regarding the telecentricity constraint. We defined the TCO, which determines that the aperture stop (APS) is floating in the system.

Because the chief ray is determined by the location of the aperture stop in the optical system, a floating APS changes the aberrations of the optical system. In the same time, we control the telecentricity on the image side by the request M 0 10 A P HH 1 and its weight within the merit function. In our design, we kept the value of the exit pupil position approximately 300 mm.

Figure 6A shows the starting point of the UV lithographic objective when the independently designed parts have been connected, giving a total length 780 mm. The model has very similar optical aberrations as the separately designed rear part of the objective.

The starting point, with 0.002 transverse aberrations, was optimized with GNO (optical path difference target) and GSR (sagittal ray aberrations). Those requests define the grid of rays whose OPDs are to be minimized, or transverse aberrations are to be controlled. The program creates a rectangular ray grid filling the entrance pupil, and weighs each ray according to optional user input. With these rays under control, the design reached the diffraction limit. The important constraints on the telecentric chief ray, F/number, and magnification were controlled within the merit function with 131 optimization variables. The diffraction-limited objective, with 660 mm length, after optimization with glass model variables, is shown in Figure 6B. It can be noticed that we have designed a two-waist UV lithographic objective with glass models.

The next design goal is to replace the glass models with real glasses suitable for use in the i-Line. There are two ways to replace the glass model: The old-fashioned way is

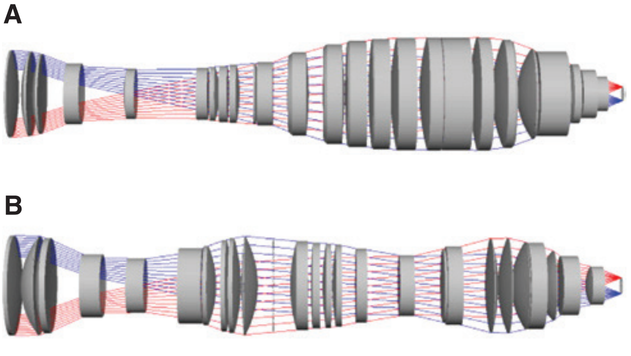

Figure 6: (A) Starting point of UV lithographic objective with glass models. (B) UV lithographic objective with glass models after optimization.

to replace the glasses manually, one by one. This basically involves a method of looking through the glass catalog and repeating the optimization many times. For the complex system as we have here, it takes around 3 h to complete this task. Another way is to use the ARGLASS (automatic real glass insertion) feature from SYNOPSYS and rely on its precision. Figure 7 examines the difference in the Strehl ratio between the lithographic objective before and after the automatic glass insertion. Graph number 1 shows the Strehl ratio over the field of the objective with glass models. Graph number 2 shows the same with real glasses sorted by ARG feature. This was done in 20 min with 50 steps of optimization. The efficiency of ARG is obvious here, especially if we consider consumption of time.

As far as we know, distortion correction can be perfectly achieved with constraints, perhaps with larger weighting at the final design stages when you have reached most of your lens design goals. As the front lens group is responsible for the larger amount of distortion (Figure 6A), it was used more for the control of distortion at the final optimization [15].

The merit function macro used for the final optimization was constructed of GO2 (optical path difference squared) ray grids and HH (ray-angle control) requests at several field points, GIHT (distortion control) at several points, and a request for telecentricity.

Figure 8 shows the final design of the UV lithographic objective with real glass material. The optical system is optimized to the diffraction limit with a Strehl ratio of 0.989 for 365 nm at the edge of field. A designed UV lithographic objective has 660 mm of total length, 25 lenses with standard surfaces, and distortion less than 0.01%. The simulated internal transmission of lithographic lens for 365 nm shows 52% after adding AR (anti-reflective) coatings.

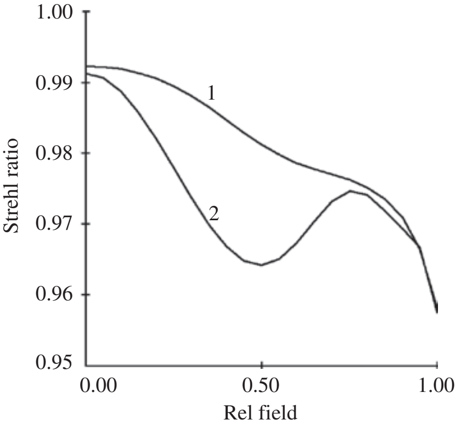

Figure 7: Strehl ratio of lithographic objective with glass model and with real glass.

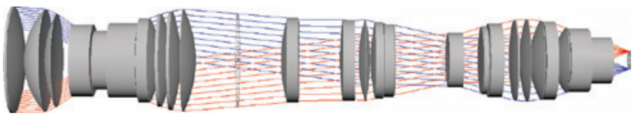

Figure 8: Designed UV lithographic objective.

4 Summary

We have presented a method for designing a UV lithographic objective, using a global search algorithm (DSEARCH) to find the starting point, and by computer optimization of that design. By showing how to obtain a successful starting design of the lithographic system with DSEARCH, we have proved that the optical designer can rely on software decisions in the several stages of the design process. In conclusion, we have addressed issues in the optimization of an optical system wherein two parts have been designed independently and then combined.

We have shown how the pupil aberrations, telecentricity, and distortion are related to each other and described a technique for dealing with conflicting constraints by judicious compromises.

This method can be used to simplify the several stages involved in the design of a lithographic optical system, or any similar, complex optical system, which consists of several lens groups. We believe that the developing of optical systems through utilization of global search features is the future of new-age optical design.

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Irina Livshits was born in the Russian Federation and graduated in the field of Optical Devices and Spectroscopy from the National Research University of Information Technologies, Mechanics and Optics ITMO (formerly named as Leningrad Institute of Fine Mechanics and Optics) with a Master's Degree in 1974. She received her Doctor of Science degree in 1980. Since 1974, she has been a Research Scientist and Educator in Optical Design at the same University at the Department of Theory of Optical Devices. Her current position is the Head of Lab "CAD of Opto-information and Energy Saving Systems". She authored 178 publications, including 70 patents. She is a member of EOS, SPIE, and ROS.

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Mr. Don Dilworth received his B.C degree from MIT University in 1962. He is president of Optical Systems Design, Inc., and has since 1961 been intensively involved in development and application of computer software for optical design. He has extensive experience in most areas of lens design, particularly in thermal infrared systems, and is the author of the well-known SYNOPSYS™ lens design program, which is widely used by lens designers worldwide. As author of SYNOPSYS, Mr. Dilworth has advanced the state of the art in the areas of artificial intelligence (AI) and with the development of the popular PSD (Pseudo Second Derivative) optimization method. He is a senior member of the Optical Society of America and SPIE. He was director of the optical design department at Baus Optics, Inc., where he developed and implemented techniques for the design of geometric and thin-film optics. Prior to joining Baus Optics, Mr. Dilworth was employed by Itek Corporation as Senior Optical Physicist. In this capacity he was responsible for designing a variety of advanced optical systems, including aerial photographic lenses used on the recently declassified Corona project, aspheric systems, multilayer dielectric coatings, and a submarine periscope. At the Massachusetts Institute of Technology, he developed computational techniques for optical and thin-film design, which were applied to the design of the optical navigation equipment for the Apollo project.

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Sergey Okishev has started his research career in the optical design of microscopes and photo-objectives at the Leningrad Institute of Fine Mechanics and Optics early. He is one of the leading specialists in the optics, optical design, and testing with more than 30 years of experience.