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Application of a global optimization process to the design of pickup heads for compact and digital versatile disks

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Abstract. A global optimization process is developed for designing an objective lens for multiple-configuration applications. As a demonstration, it is shown that diffraction-limit performance can be achieved for a pickup head used for both compact disks (wavelength 780 nm) and digital versatile disks (wavelength range 635 to 650 nm) with different working distances and focal lengths, at a numerical aperture of 0.6. [DOI: 10.1117/1.2361281]

Subject terms: pickup head; optical design; optimization.

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Numerical optimization applied to complex problems has been an important field of science and technology. Application of various algorithms to a variety of topics can be found in the literature.[1] System and performance optimization of optical design to meet particular requirements has been one of the classical applications of numerical optimization, and it is nontrivial in that its adjustable parameters are numerous and the response of the merit function to variation of the system parameters is very nonlinear. However, a well-designed algorithm can provide a useful method to find the best solution for a sophisticated system even with a large number of variables. Studies of optimization in optical system design can be traced back to early 1960, when computers were starting to be used.[2] Among many released algorithms, the method of damped least squares (DLS) has been widely used and become a standard scheme for approaching a minimum.[3] However, the DLS approach is only a method of local optimization, because of its search strategy. To handle the dramatically emergent fields of technology, new searching strategies are strongly demanded, while, on the other hand, better theoretical understanding of the nature of optimization is desired for further exploration. For these purposes, recently, Koshel utilized the simplex algorithm to optimize illumination design, which is a large and difficult area in which more research is strongly required,[4] and Bociort, van Driel, and Serebriakov tried to realize the connection of local minima over the whole variable space.[5] Generally, it can be acknowledged that the performance of local optimization depends greatly on the choice of initial design and the definition of merit function. For real applications, even with an available paraxial solution, it may not be easy to achieve a proper initial design, which can lead to the best solution or even one with diffraction-limited performance in imaging optics. Hence, a nonlocal, or even global, optimization algorithm is demanded for seeking a better solution within a constrained domain of variables. Evidently, the situation becomes much more complicated for zoom lenses or optical systems with multiple configurations.[6]

As a real illustration of multiple-configuration applications, we consider the pickup-head lens design for compact disks (CDs) and digital versatile disks (DVDs), which has attracted much attention in recent years.[7–11] In those studies, holographic optical elements (HOEs)[8] and complex-surface designs[7,9–11] were proposed to solve the compatibility problem of applying a single lens for two different wavelengths. With the progress of manufacturing technology, aspheric lenses are no longer impossible to fabricate. Naturally, a singlet lens with aspheric surfaces will be taken as a solution for the design of two-wavelength optical pickup heads. However, the need for different ranges of wavelengths, thicknesses of cover materials, and other optical and mechanical specifications raises difficulties in finding suitable coefficients for aspheric surfaces with the desired performance, which generally means diffraction-limit performance for all configurations. Nevertheless, the solution may be obtained with the aid of a well-developed global optimization process as shown below. In this paper, we design an objective lens with CD/DVD double specifi-

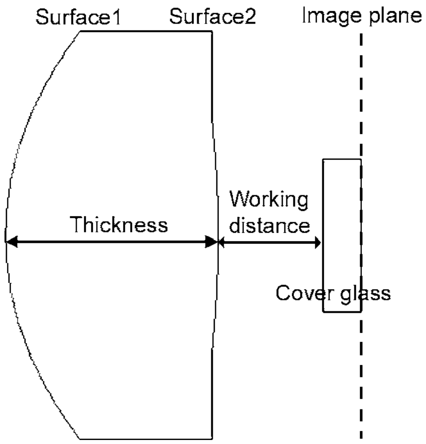

Fig. 1 Schematic of lens layout.

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Table 1 Specifications of the DVD/CD pickup.

Specification	DVD	CD
Wavelength (nm)	635–650	780
Focal length (mm)	3.36	3.39
Numerical aperture	0.6	0.6
Working distance (mm)	1.71	1.35
Cover glass thickness (mm)	0.6	1.2

cation as a demonstration of the application of a global optimization process.

A higher numerical aperture (NA) of 0.6 and shorter wavelengths (635 to 650 nm) than for the CD ($NA=0.45$, $\lambda=750$ nm) are necessary for the DVD in order to increase the data density. However, a higher NA will also increase the coma, which is proportional to (NA),^{3} and the thickness of the cover materials. Thus, the substrate thickness adopted for the DVD was half that of the cover materials used for the CD. Table 1 shows the specifications of the CD and DVD pickup lenses, which constitute our design target for the single aspheric lens. A schematic diagram of lens layout is shown in Fig. 1. In this optimization, the NA for a CD is chosen as 0.6 instead of 0.45, the regular requirement. The higher NA reflects the larger lens area that is needed for a single objective lens operated at two distinct wavelengths; to increase the NA for a CD means to take the outer region of the lens into consideration for both DVD and CD configurations, and this will tighten the specifications and increase the difficulties in optimization.

A well-defined merit function is able to reflect the required performance and to drive the algorithm to find the optimal results efficiently and effectively. Such a merit function may have to be quite nontrivial and special. However, for a global optimization, the merit function should be of general purpose. For the design of an optical pickup lens, the most crucial criterion, beyond the specifications listed

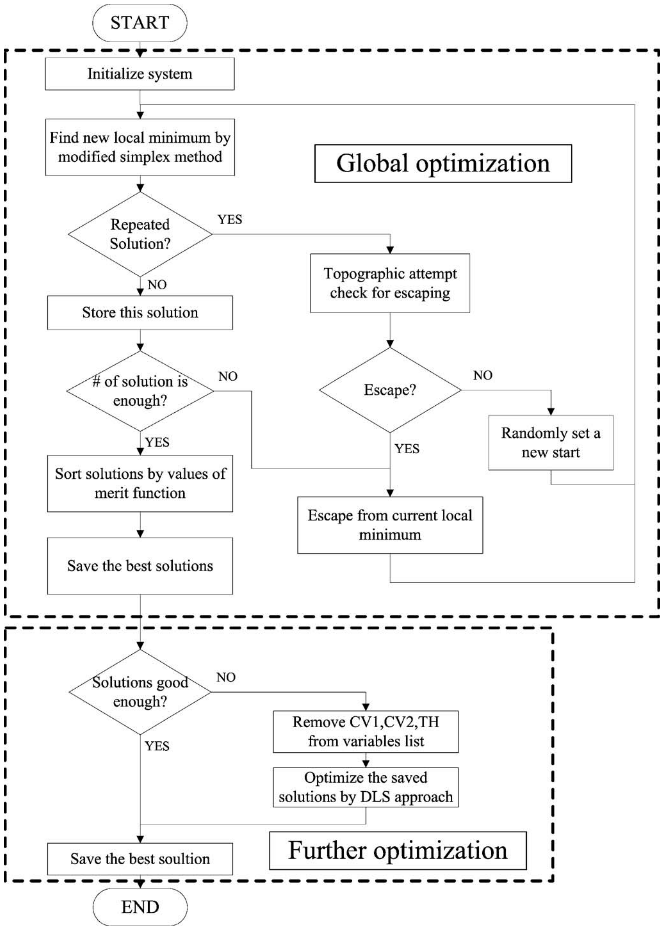

Fig. 2 Flow chart of optimization process.

Table 2 List of the variables used in global optimization and their boundaries.

Variable	Lower limit	Upper limit	Definition
CV1	−1	1	Curvature of surface 1
TH	1	5	Thickness of lens
CV2	−1	1	Curvature of surface 2
CC1	0[a]	0[a]	Conic constant of surface 1
CC2	0[a]	0[a]	Conic constant of surface 2
AD1, AE1, AF1, AG1	0[a]	0[a]	Aspheric coefficients of surface 1
AD2, AE2, AF2, AG2	0[a]	0[a]	Aspheric coefficients of surface 2
WD1	1.65[b]	1.75	Working distance for configuration 1
WD2	1.3	1.4	Working distance for configuration 2

[a] Lower limit=upper limit=0 means no bound for variable.

[b] Limits of working distances are roughly decided by specification: ±3.7%.

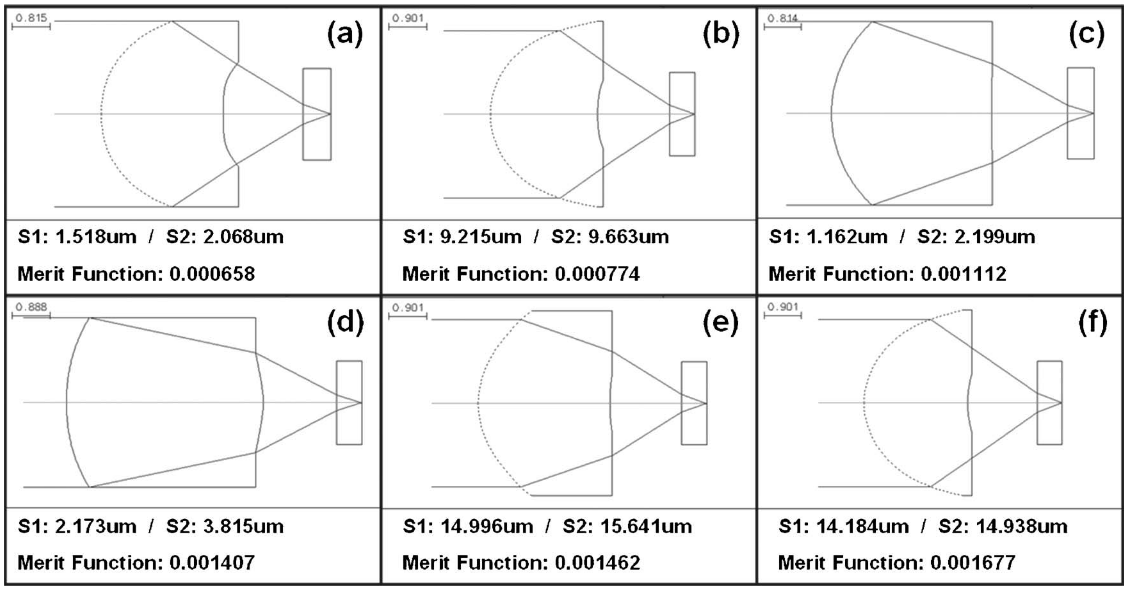

Fig. 3 Best six solutions of global optimization for the DVD configuration, with the simulated spot sizes and values of the merit function. S1 and S2 denote the average spot sizes for the CD configuration and for the DVD configuration, respectively.

in Table 1, is the spot size, which indicates the radius of the distribution of energy focused on the focal plane by the objective lens. Thus, the root-mean-square (rms) spot sizes produced by the two configurations on the focal plane were taken as a part of our merit function for the judgment criterion of optimization. Besides the spot sizes, the focal lengths of two configurations are also included in our merit function to ensure that the final design is able to meet the mechanical constraints. Thus, the merit function we took had the form

$$M = \sum_{i}^{\text{no. of configurations}} \{[w_f(\mathrm{EFL}_i - f_i)]^2 + (w_s S_i)^2\}, \tag{1}$$

where w_f and w_s are the specified weight; EFL, f, and S are the determined focal length of the system, the target focal length, and the determined rms spot size, respectively; and the summation index i labels the configurations. The weights for effective focal length and spot size are different—in the current demonstration, the former is 0.1 and the latter is 1—in order to balance the contributions of the terms in the optimization. It should be noticed that the definition of the merit function reflects the deviation between the current performance (effective focal length and rms spot size in our case) and the expected performance. Consequently, our target is to minimize the value of the merit function. From this point of view, we can recognize it as an error function instead of a merit function.

To make the spot sizes at the two wavelengths small enough, especially for large numerical apertures, an aspheric surface is introduced, whose parameters are variables in addition to the curvatures and thickness of the lens. The most common aspheric surface is of the form

$$z = \frac{\mathrm{CV}\, r^2}{1 + [\sqrt{1 - \mathrm{CV}^2(\mathrm{CC} + 1) r^2}]^{1/2}} + \mathrm{AD}\, r^4 + \mathrm{AE}\, r^6 + \mathrm{AF}\, r^8 + \mathrm{AG}\, r^{10}, \tag{2}$$

where z is the surface sag, CV is the curvature of the surface, CC is the conic constant, and AD, AE, AF, and AG are the aspheric coefficients of higher-order terms of radius r. Table 2 shows the list of variables and their bounds for global optimization. A total of 15 degrees of freedom characterize the space of variables. It is noticed that the values chosen for the bounds on the working distances for the two configurations are necessary and could be very critical, since we have to consider both the specification and the budget for optimization. Practically, the working distance is

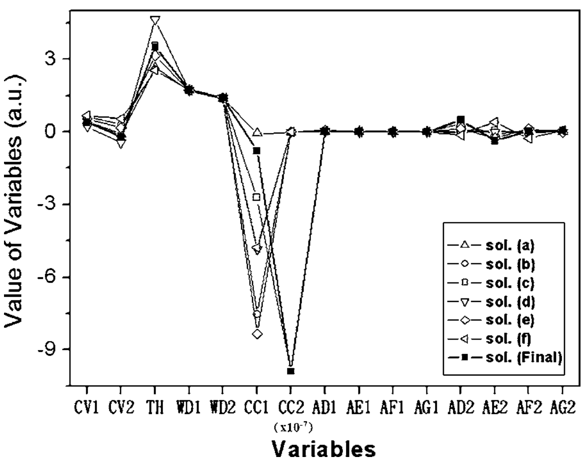

Fig. 4 Parameter variations of the six preliminary solutions and the final design.

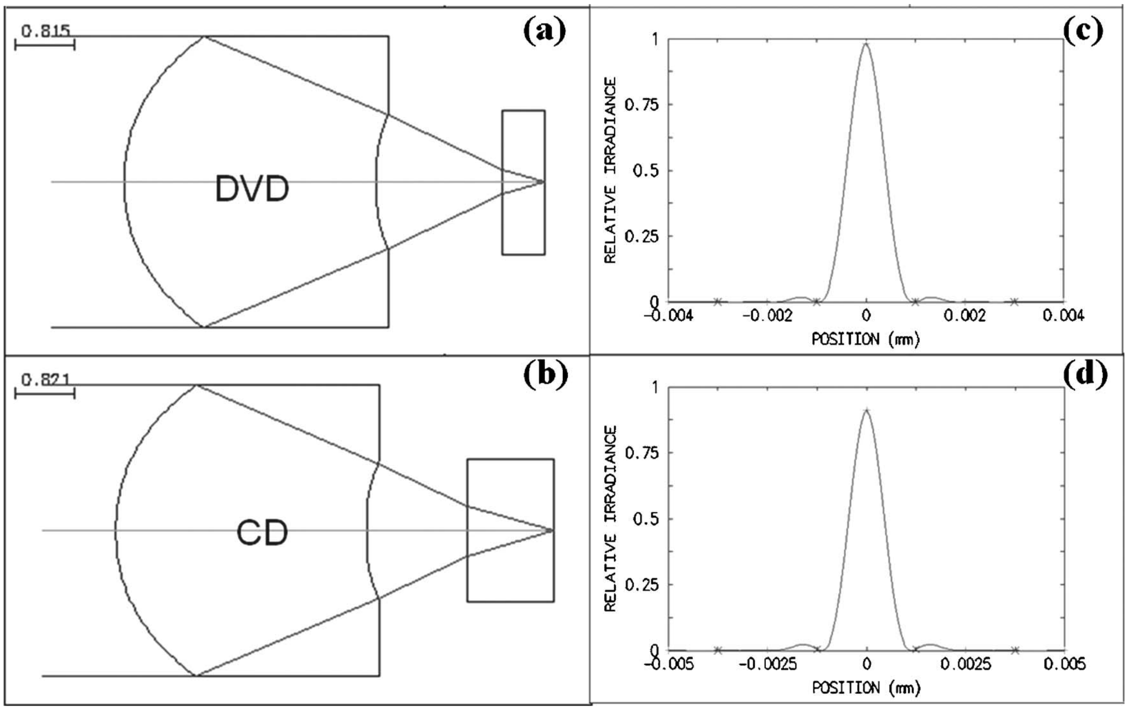

Fig. 5 The layout of the final design, where (a) is for the DVD and (b) is for the CD pickup. The corresponding point spread functions are shown in (c) and (d), respectively.

one of the mechanical specifications, and its limits are determined by the budget. Including the working distance among the system variables enables us to assure that the final design will not deviate from the desired specification and also provides new degrees of freedom to optimize the design of the CD/DVD objective lens.

For a complex optical design problem, even if the best solution can be found by a global search algorithm, it still takes large computational power. To make a useful but quick search, a method combining proximate and stochastic search, so that a topographic map with adjustable resolution (*topographic attempt*) can be achieved, has been developed as illustrated in Fig. 2. To perform such an exploration, an efficient check of multiple trial solutions is demanded. In this respect, the simplex method contributes superior capability of exploring solutions, because randomly sampling $N+1$ points in the N-dimensional design space provides a chance of hitting another local minimum in the neighborhood of the initial location; in contrast, a gradient-dependent local optimization algorithm can easily be trapped at a particular local minimum if the initial point is fixed.[12] Our global optimization algorithm utilizes a modified downhill simplex method for local minimum search and a hybrid algorithm combining topographic attempts and stochastic searching to randomly explore local minima in the value domain of the merit function. Among the components of the merit function, the deviations of effective focal length and rms spot size could be extremely large when an unreasonable design has been generated, which requires bounds on the space of reasonable designs. Consequently, it is possible that the optimizer will be trapped in a limited proximity region. Once this happens, a random

Table 3 The optimized parameters for the DVD/CD dual-purpose lens design.

Parameter	Value	Parameter	Value
CV1	0.390281	AG1	−0.000115
CV2	−0.213145	AD2	0.484489
TH	3.499182	AE2	−0.379871
CC1	−0.781059	AF2	0.032930
CC2	−9.9047e+07	AG2	0.040510
AD1	0.023906	WD1	1.733523
AE1	−0.004754	WD2	1.400000
AF1	0.001182		

Table 4 Comparison of specification and optimized results.

	DVD			CD		
Parameter	Spec.	Optim.	Diff. (%)	Spec.	Optim.	Diff. (%)
Focal length (mm)	3.36	3.36378	+0.125	3.39	3.3862	−0.112
Working distance (mm)	1.71	1.7335	+1.37	1.35	1.4	+3.7

casting mechanism is necessary to throw the optimizer to a new start position. There is inevitable risk that the new start position will be an unreasonable design; thus either prechecking the value of the merit function for the new start or an *enforcement* operation[13] will be useful to move the optimizer to a new reasonable and effective initial design.

We adopted OSLO, commercial software for optical simulation with flexible programming capability,[14] as the platform on which all algorithms are developed. A global search algorithm was employed to look for the local minima within the design space of 15 dimensions, which is limited by bounds on each variable. It is found that with only one trial run, the desired designs can be deduced. Nevertheless, as a detailed evaluation, extensive results corresponding to local minima in the space of the merit function were obtained by the optimization algorithm, and the best six sets with the lowest value of merit function are shown in Fig. 3. For simplification, only the results of configuration 1 (designed for the DVD specification) are presented. In effect, this quick search is to identify the dominant *complex* where optimized solutions can be found. Indeed, the spot-size analysis of those six sets of variables shows that the complexes indicated by these solutions include good initial designs for further improvement.

As shown in Fig. 4, the major differences among these designs are in the curvatures and the thickness of the lens, which determine the optical power of the lens. In other words, the proposed optimization scheme is superior in localizing the design to the specified optical power. Generally, in influencing the optical performance, the conic constants are in competition with all the other aspheric coefficients. It is worthwhile to notice that the conic constants are also different in different designs, and this means that the proposed optimization is directly involved in tuning the conic constant, and hence the aspheric coefficients are less different for the six designs. It is also interesting to note that the working distances are nearly the same.

In the next stage, the simplex method was replaced by the usual DLS method for approaching the local minimum, because the solutions have been confirmed to a complex. Doing DLS approaches for these six new initial designs will reach our design goal if the curvatures of surfaces 1 and 2, the thickness of the lens, and the working distances are removed from the list of variables of optimization. The reason for removing the first three variables is physical: the curvatures and thickness determine the optical power of a lens. Either the focal length or the spot size will be strongly affected by changing these three parameters. Removing them cannot only decrease the complexity of variable domain but also return the emphasis to other aspheric coefficients during optimization, which leads to higher performance.

The best result, which is deduced from the preliminary design shown in Fig. 3(c), can be obtained by the same further optimization process among the six preliminary results is shown in Fig. 5, and the optimized parameters of the lens design are listed in Table 3. We have a set of parameters, which can achieve focusing of the collimated incident beam with wavelengths of 635 to 650 nm and 780 nm on the image plane with minimum rms spot size and meet the specifications. The geometrical-optical estimate of the rms spot size at wavelengths of 635 to 650 nm is 0.491 μm and that at a wavelength of 780 nm is 0.84 μm. They are both less than the theoretical diffraction limits, which are 0.918 and 1.094 μm, respectively. In this case, a diffraction-based verification is necessary. Figures 5(c) and 5(d) are graphs of the point spread functions of the corresponding cases. From them it is obvious that the energy is almost all concentrated in a very small range with diffraction-limited performance, because both the Strehl ratios are larger than 0.8.

Table 4 shows the comparison of the required specifications and the results of the final design. It can be seen that the design can reach the specifications within the range of allowance.

In conclusion, we have successfully demonstrated a process combining global and local optimizations, mainly with a modified downhill-simplex algorithm, by which a dual-purpose CD/DVD pickup head was designed with diffraction-limited performance in both configurations. The optimization is achieved through aspheric coefficients. This study also shows that the computer-aided design with appropriate algorithms and optimization methods will be very helpful in advancing the development of emergent technology and applications for optical system design.

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